CHARLES RIVER WATERSHED STUDY

WATER RESOURCES

INTERIM MEMO NO. 1

STONY BROOK SUB-WATERSHED

DEPARTMENT OF THE ARMY
NEW ENGLAND DIVISION, CORPS OF ENGINEERS
WALTHAM, MASS.

DECEMBER 1967

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SYLLABUS

The current program of water resources utilization in the Hobbs Brook Sub-watershed is analyzed Proposals for improved utilization of available water are evaluated. Water availability is determined using a hydrologic analysis applied to data supplied by the City of Cambridge Water Department. Surface runoff was estimated by processing the Cambridge data with a digital computer

Alternatives are analyzed by simulating the operation of the system over a twenty year period. Economic evaluations are based upon the simulation study.

Discussions of political, administrative and legal problems associated with the future of the Hobbs Brook system are included.

The major conclusions were:

1. Hobbs Brook Reservoir may prove eligible for combined use as a water supply and limited recreation reservoir.

2. No program of major system alteration involving construction can be economically justified.

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CHARLES RIVER WATERSHED

Interim Report No. 1

I. INTRODUCTION

The purpose of this report is to study the current water utilization of the Stony Brook Sub-watershed with a view to establishing whether improvements are possible from an engineering or water availability standpoint, and whether such improvements are desirable in the light of economic and political considerations.

The Stony Brook Sub-watershed is one component of the Charles River Watershed which is in turn part of the North Atlantic Region. In addition, demographically, the sub-watershed is part of a growing urban region. The towns lying therein are all considered Boston suburbs. Consequently, problems of local water resources management and planning are compounded by the local urbanization trend.

One of the major problems of the North Atlantic Region has been the occurrence of droughts, coupled with an increasing demand for water in the urban centers. Water rationing has been required in order to conserve a limited supply. Historically, the region had always been considered a water surplus area. Competition for available supplies existed only on occasion and were localized. A by-product of the post-war economic prosperity has been an increased demand upon existing water resources to such an extent that competition for water now is general. Urban centers are in the position of competing with each other for remote water resources.

In order to effectively manage the nation's water resources on the required interstate scale, the Federal Government has directed its agencies to study the problems and to make recommendations, which after appropriate review become the basis of enabling legislation. The recommendations are based upon the application of modern methods of engineering and planning. These include the traditional disciplines of hydraulic engineering, as well as techniques of evaluation which have grown out of what is called systems analysis or systems engineering.

An attempt has been made in the current study to provide an approach consistent with the principles of the analysis of the larger systems. One of these principles is that water, as a natural resource, should be conserved. Conservation implies a program of maximum utilization for human use. Consequently, in a local study such as this one, an attempt is made to establish whether the local system is surplus or deficit with respect to demand vs. supply of water. A deficit must be met by conveying water from other watershed areas, while a surplus may be utilized to help supply demands elsewhere in the larger system.

There is usually a complex set of laws associated with the allocation of water. These may be Federal, state, or local contractual obligations. In a dynamic regional environment, laws that were adequate when enacted sometimes inhibit new developments which are clearly in the public interest. One of the study objectives is to establish evidence supporting what the public interest is from an engineering and systems analysis approach. Specific suggestions for resolution of legal problems engendered by planning proposals is however outside the scope of the study.

II DESCRIPTION OF STUDY AREA

A. Location, Topography, and Geology

Figures II-1 and II-2 define the study area. Most of the Stony Brook Watershed is zoned as one family residential units with a small portion allocated for industrial use. The Towns of Lincoln and Weston, comprising 76.5% of the watershed, require one or two acre lots and have inaugurated effective programs of space conservation. Waltham and Lexington exhibit a more pronounced urbanization trend than Lincoln and Weston and comprise the remaining 23.5% of the area if Hobbs Brook Reservoir is included, and 19.4% otherwise. Consequently, future developments in these towns may influence the quantity and quality of a substantial portion of the surface runoff collected by the Hobbs Brook and Stony Brook Reservoirs.

Topographically the area is hilly, the highest elevation exceeding the 400 foot contour, while the elevation at Stony Brook Reservoir is approximately 80 feet. Stony Brook, which drains most of Lincoln, is joined by Cherry Brook which drains the northern half of the part of Weston lying in the watershed. The balance of Weston is drained by Stony Brook and smaller brooks which run into the Stony Brook Reservoir The Lexington section is drained by the Hobbs Brook Reservoir while the Waltham section drains into both reservoirs.

TABLE II-1

Area of Portions of Towns

Comprising the Stony Brook Sub-Watershed

	Area (sq. miles)	% of Watershed
Lincoln	9.2	39.0
Weston	8.7	36.9
Waltham	3.9	16.5
Lexington	1.8	7.6
	23.6	100%

Geologically the region is characterized by glacial till within an average depth estimated at 15 feet. The clay content is low. Therefore, the soil is considered favorable as a medium for groundwater aquifers. The extensive swamp areas constitute means of natural replenishment of the groundwater table. During periods when the reservoir levels are below the adjacent groundwater levels, subsurface runoff may constitute a significant source of supply to the reservoirs.

B. Climatology

The watershed is part of the Boston metropolitan area. Consequently it presumably has similar long range weather characteristics although there will be differences on a day to day basis. Generally, temperatures will be slightly lower in the winter and higher in the summer than for Boston. Total monthly precipitation may be assumed the same as measured at Logan Airport in Boston although large daily differences probably exist, especially during the summer.

A weather bureau summary of Boston climatological data is given in Table II-2a and II-2b.

C. Water Utilization

Cambridge, Lincoln, and Weston are all consumers of water collected by the study area. Lincoln and Weston depend almost exclusively upon groundwater sources while Cambridge obtains its supply by managing the Hobbs Brook and Stony Brook Reservoirs. Current (approximate) daily water consumption reported by the towns are:

Cambridge	25.0	million gallons/day
Lincoln	0.8	million gallons/day
Weston	0.95	million gallons/day

Lincoln is supplied by a single well in the vicinity of Beaver Pond near Tower Road six days a week and from surface water in Sandy Pond one day a week.

Weston is supplied by several wells and further augments its water needs with purchases from the MDC (Metropolitan District Commission). The well at Kendall Green, near the junction of Cherry Brook and Hobbs Brook, is the only one that draws upon groundwater in a manner that may compete with the replenishment of Stony Brook Reservoir during periods of low flow. In 1964 the Kendall Green well supplied an average of .23 million gallons per day which is the maximum recorded.

Lincoln and Weston are not sewered. The town planning commissions do not anticipate a need for constructing a sewer system. Sanitary domestic sewage is returned to the ground via individual cesspools or septic tanks. Consequently the demand upon local water resources is considered non-consumptive.

The only significant consumptive user is Cambridge. Most of the Cambridge demand is met by the watershed area. Occasionally Cambridge buys water from the MDC. The reservoirs are operated in a manner designed to minimize the quantity of water that must be purchased. All water is treated at the Fresh Pond treatment plant, excluding water purchased which is not treated.

The reservoirs are reserved exclusively for water supply to the City of Cambridge. No recreational use is presently permitted although some fishing does take place informally.

During the spring runoff of most years of record, the two reservoirs filled and excess water discharged via a spillway at the Stony Brook Dam into the Charles River.

Cambridge consumption per capita (269 gal/cap/day) reflects heavy non-domestic demands peculiar to Cambridge. When one considers the "hidden population" which includes several thousand students not included in the census, and the institutional and industrial water users, the figure does not appear unreasonably high.

TABLE II-2a

AVERAGE TEMPERATURE

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	An'l.
1930	31.8	34.1	38.3	47.6	59.4	72.4	72.6	70.5	69.4	53.0	45.0	33.2	52.3
1931	30.6	30.6	39.3	50.2	60.3	67.2	74.0	72.2	66.9	58.5	49.4	36.6	53.0
1932	38.8	30.6	35.6	47.4	60.2	66.4	72.8	74.0	65.2	57.1	42.8	38.1	52.4
1933	37.8	33.7	35.7	46.5	61.6	69.6	70.8	71.8	65.8	52.7	38.3	26.8	50.9
1934	29.6	17.5	35.1	48.0	60.6	66.9	73.2	67.3	64.6	49.6	45.6	28.4	48.9
1935	23.2	27.8	38.4	45.2	55.5	65.5	72.6	70.7	61.4	53.8	45.4	27.1	48.9
1936	28.2	22.8	41.8	45.2	60.6	66.2	71.1	69.7	62.6	54.4	39.5	35.0	49.8
1937	37.4	33.2	34.1	45.2	59.1	66.4	73.2	74.6	63.0	52.6	44.0	31.2	51.2
1938	28.0	30.6	39.1	48.7	55.8	67.2	71.8	73.6	62.2	56.0	46.4	34.0	51.1
1939	27.8	32.2	33.2	43.6	56.4	65.6	72.3	73.8	64.5	54.2	40.8	33.4	49.8
1940	23.0	29.6	33.1	43.6	56.2	65.1	71.6	68.4	63.3	50.6	42.9	34.3	48.5
1941	25.2	29.4	33.4	51.6	59.8	68.2	71.4	70.6	66.0	55.9	48.0	35.2	51.2
1942	28.6	27.0	40.8	49.7	60.8	67.4	71.1	70.7	64.6	55.8	43.5	28.6	50.7
1943	25.5	30.6	36.0	43.4	57.6	71.2	74.1	71.0	63.0	53.8	43.3	29.6	49.9
1944	31.0	29.6	34.1	44.6	63.2	67.0	73.8	74.7	65.0	53.8	43.2	30.8	50.9
1945	23.8	30.5	46.3	52.5	55.2	66.6	71.9	70.8	67.1	53.1	45.5	28.5	51.0
1946	28.4	27.6	47.2	46.2	58.0	67.5	70.8	67.8	65.8	58.4	47.8	34.8	51.7
1947	32.6	29.6	37.7	47.2	56.9	65.4	74.4	73.2	64.8	61.6	41.2	30.4	51.2
1948	23.4	26.6	38.0	48.0	55.0	63.6	74.5	73.7	65.7	54.2	49.6	36.3	50.7
1949	34.6	34.4	39.2	50.8	60.4	71.6	76.2	74.4	63.2	58.4	43.5	36.8	53.6
1950	36.2	28.0	33.7	46.8	55.8	69.1	73.5	70.9	61.5	56.3	47.8	35.5	51.3
1951	34.0	34.7	39.1	51.0	59.1	66.0	74.0	70.7	65.6	54.8	42.6	35.0	52.2
1952	32.6	32.5	37.2	50.5	57.2	70.7	77.5	72.3	66.3	53.0	44.9	35.7	52.6
1953	34.7	35.0	39.1	48.9	58.4	70.5	73.2	72.0	66.3	56.2	48.6	40.2	53.6
1954	26.0	36.4	38.8	50.1	56.3	66.6	72.2	70.1	63.2	58.6	44.4	34.4	51.4
1955	28.5	32.0	37.6	49.2	62.8	66.8	77.2	74.5	64.5	55.1	41.9	26.6	51.4
1956	30.6	32.5	33.6	45.6	55.4	68.9	71.7	71.9	61.1	54.4	46.1	36.0	50.7
1957	23.4	34.7	39.1	49.4	59.9	71.3	74.1	69.3	67.3	54.6	47.2	40.0	52.5
1958	31.0	25.5	39.1	48.8	56.6	63.9	72.4	72.4	64.6	52.6	46.6	26.4	50.0
1959	28.7	26.7	37.0	49.0	62.6	64.6	74.7	74.1	68.1	55.1	44.4	36.3	51.8
1960	30.9	35.3	32.7	48.3	59.7	69.6	73.1	72.1	63.7	53.9	48.0	29.5	51.4
1961	25.0	31.6	36.8	45.3	56.3	68.9	72.1	72.5	69.0	57.3	44.6	32.8	51.0
1962	28.7	26.7	38.5	49.4	57.2	68.4	70.4	70.0	62.9	54.1	41.7	30.0	49.8
1963	29.5	25.9	39.1	48.9	59.4	69.5	74.7	70.4	60.8	60.0	48.3	25.9	51.0
1964	31.7	29.1	38.7	46.1	60.3	67.1	71.5	66.4	62.0	52.5	44.1	32.4	50.2
1965	25.4	28.0	35.8	44.2	59.5	67.4	71.0	70.5	62.5	52.8	42.1	36.1	49.6
RECORD MEAN TEMP	28.8	29.0	36.8	46.8	57.8	66.9	72.4	70.5	63.9	54.1	43.3	32.4	50.3
MAX	36.4	36.8	44.3	54.9	66.5	75.7	80.8	78.5	71.9	62.1	50.5	39.5	58.2
MIN	21.1	21.2	29.2	38.7	49.0	58.1	64.0	62.5	55.9	46.0	36.0	25.3	42.3

TABLE II-2b

BOSTON, MASSACHUSETTS
LOGAN INTERNATIONAL AIRPORT

TOTAL PRECIPITATION

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1930	2.77	2.23	3.02	2.08	3.39	2.24	3.36	3.03	0.26	5.83	4.09	2.99	35.29
1931	4.09	4.21	4.66	3.12	4.51	9.13	2.43	4.45	1.67	2.18	0.82	2.90	44.17
1932	4.24	1.74	5.28	1.67	1.63	2.05	2.10	4.24	4.50	7.18	5.24	1.78	41.65
1933	2.04	3.77	6.80	7.37	2.74	1.22	2.63	3.41	10.94	3.11	0.65	2.93	47.61
1934	2.67	4.45	4.04	3.21	1.56	3.11	1.25	1.83	5.67	2.94	1.78	1.64	34.15
1935	6.13	3.26	1.52	4.77	1.35	5.07	1.10	2.14	2.69	0.34	3.91	0.66	32.94
1936	6.46	3.66	6.40	3.54	1.70	2.37	1.04	5.15	3.79	2.67	1.33	8.19	46.30
1937	3.93	1.31	3.57	5.34	2.52	3.47	1.17	4.97	3.69	3.95	4.66	5.09	43.67
1938	4.91	2.38	2.42	3.22	4.42	6.30	9.46	3.31	6.00	2.43	2.89	2.80	50.54
1939	2.18	3.79	5.23	4.54	1.29	2.70	0.75	2.14	1.01	4.77	1.14	2.91	32.45
1940	1.68	4.78	3.83	4.58	3.28	1.80	3.17	0.85	2.32	0.76	6.24	2.76	36.05
1941	4.21	1.70	3.40	1.70	2.43	4.29	2.90	1.55	1.18	1.92	2.40	3.19	30.87
1942	3.69	3.45	7.01	1.59	2.11	4.24	4.14	2.09	1.96	2.78	4.69	4.72	42.47
1943	3.74	1.23	4.02	2.64	4.56	1.49	3.91	1.28	1.41	4.82	2.16	0.99	32.25
1944	2.03	2.15	3.92	3.52	0.25	5.35	1.61	1.79	5.36	2.58	5.68	2.83	37.07
1945	3.67	4.09	1.90	2.02	4.47	6.44	2.12	4.27	1.81	2.23	6.86	7.42	47.30
1946	4.18	3.00	1.50	2.62	4.91	2.76	2.22	9.92	2.04	0.34	0.98	3.60	38.07
1947	2.45	1.44	2.30	4.15	4.36	2.88	3.98	2.19	3.95	1.13	5.13	3.95	37.91
1948	5.11	2.08	3.14	2.62	5.37	4.50	4.53	1.24	0.67	4.84	5.16	1.25	40.51
1949	3.21	3.25	1.66	3.23	2.53	0.93	1.10	2.12	6.47	1.60	3.71	1.64	31.45
1950	3.86	3.81	2.99	2.38	1.55	1.10	1.45	3.14	0.89	1.99	6.17	3.37	32.70
1951	4.04	3.71	4.41	3.06	4.81	4.31	2.13	3.23	2.00	3.98	6.60	4.69	46.97
1952	4.31	4.71	4.41	4.41	3.57	3.26	0.52	6.86	1.13	1.61	1.72	4.09	40.60
1953	6.28	4.14	11.00	6.04	5.06	0.48	2.76	1.81	2.50	4.91	7.66	5.09	57.73
1954	3.26	3.37	3.33	5.25	13.38	2.78	2.50	5.64	8.31	3.58	5.52	5.40	62.32
1955	0.92	4.11	5.42	4.12	0.99	3.52	4.28	17.09	2.40	6.94	5.68	1.03	56.50
1956	6.99	4.36	5.39	2.94	1.85	2.03	3.32	1.46	5.07	4.39	3.46	6.13	47.39
1957	2.47	1.34	3.38	3.78	3.63	1.62	0.64	1.71	0.35	2.67	5.75	6.58	33.92
1958	9.54	5.87	4.48	7.82	4.45	2.96	3.91	5.37	7.50	4.62	3.35	1.78	61.65
1959	2.72	3.45	5.81	4.44	1.24	8.63	8.12	2.93	0.63	4.60	4.20	4.84	51.41
1960	3.04	4.84	3.23	3.51	3.80	3.46	5.18	1.64	5.97	2.48	2.49	4.82	44.46
1961	2.92	4.94	4.71	6.59	4.51	1.67	3.29	3.17	7.04	2.46	3.18	3.36	47.84
1962	3.11	4.16	1.48	3.85	1.86	2.33	1.61	3.72	4.10	8.68	3.80	4.53	43.23
1963	3.13	2.60	4.39	1.48	2.86	1.92	1.72	1.67	3.05	1.25	7.74	3.03	34.84
1964	4.56	4.67	3.48	3.69	0.53	1.91	3.12	1.78	2.65	2.82	2.18	5.08	36.47
1965	2.64	3.17	2.22	2.32	0.93	2.99	0.55	1.48	2.01	1.59	2.08	1.73	23.71
RECORD MEAN	3.63	3.34	3.84	3.60	3.21	3.12	3.23	3.64	3.21	3.29	3.79	3.46	41.36

Record mean values above (not adjusted for instrument location changes listed in the Station Location table) are means for the period beginning in 1872 for temperature and 1871 for precipitation.

D. Population

TABLE II-3

	1930	1940	1950	1960	1965#	1980*
Cambridge	113,643	110,879	120,740	107,716	92,677	93,000
Lincoln	1,493	1,783	2,427	5,613	4,463	6,500
Weston	3,332	3,540	5,026	8,261	9,848	12,000
Waltham	39,247	40,020	47,187	55,413	57,134	60,000
Lexington	9,467	13,187	17,335	27,691	31,388	38,500

Source: Federal Census

State Census

* Projection by Corps Urban Planners related to EMRPP (Eastern Mass. Regional Planning Project) and MAPC (Metropolitan Area Planning Council) forecasts.

III. STUDY PROPOSALS FOR IMPROVED UTILIZATION

A. Need for Improved Utilization

1. Cambridge Water Supply

An analysis of the water budget of manageable surface water indicated that in any random water year there is a 60% probability that Cambridge will not be able to collect a quantity equal to the demand. This analysis is based upon 110% of actual Cambridge demands from November, 1965 to October, 1966, and a hydrologic study of the runoff to the reservoirs.

TABLE III-1

Projected Cambridge Water Demand
(Million Cubic Feet)

November	90	May	94
December	92	June	100
January	90	July	112
February	85	August	112
March	96	September	94
April	86	October	93

Based upon 110% of demand November 1965 to October 1966.

Reference is made to Figure III-1 for the pattern of deficit and surplus years. With the exception of 1954-1960, the record is basicly deficit. In each year the quantity of deficit represents the minimum quantity (neglecting over-year storage) of outside water (i.e. MDC) that Cambridge would have to purchase. In the event of spillage during any of these years, the quantity purchased would be increased by the amount spilled.

Improved utilization for domestic supply purposes would consist of a program of reservoir management that would eliminate or at least minimize spillage. This will be established in a later chapter by an analysis of the system water budget on a monthly basis.

2. Recreation

In a growing urban region available expanses of open water become important components of an area recreation plan. When such waters are part of a domestic water supply system, a conflict is generated. Any recreational use of a public water supply reservoir increases the danger of serious pollution. Therefore plans for combined use of a reservoir should include a program of recreation management that assures the safety and potability of the water for domestic consumption.

The Hobbs Brook Reservoir would be a welcome addition to the region's recreational resources. The shores and some of the surrounding hills could become public park land. Recreational use may be limited to fishing, sailing, and picnicking. Boats could be restricted to sailboats, canoes and rowboats. By excluding motorboats and swimming the largest sources of recreational pollution are removed.

Problems of administering and financing a public park development for Hobbs Brook Reservoir are outside the scope of this report which merely seeks to establish the feasibility of combined water supply-recreation use from an engineering point of view. A further discussion of problems of combined usage is reserved for a later chapter.

3. Low Flow Augmentation

During periods of low flow in the Charles River a public nuisance is sometimes created by the excessive pollutional level. At present the Public Health Department may request the MDC to release a maximum of 67 million cubic feet of water to augment the low flow. MDC supplies this water only when it is judged to be surplus at a nominal rate ($10.00/million gallons). During 1965 and 1966, such surplus was not available.

It seems useful, therefore, to inquire whether a sub-watershed such as the Stony Brook system could be managed in a way that would contribute to low flow augmentation.

B. Methods for Improving System

1. Operating Rules

An attempt will be made to develop operating rules that would guarantee the City of Cambridge a maximum yield while maintaining Hobbs Brook Reservoir at a recreational pool during the summer. At the same time an attempt will be made to shift the spillage (if any) of excess water from the spring runoff to the summer months when low flow augmentation is desired.

2. Additional Storage

Additional storage could be achieved by adding a reservoir to the system or increasing the size of existing reservoirs by excavation or construction. Spy Pond in Arlington was initially considered as a possible addition to the system. It was at one time part of the system, and some conduits are still in place. In view of the low head differential between Spy Pond and Fresh Pond and the necessity for rapid transfer of water, use of this facility would require two way pumping.

There are three considerations that preclude this alternative. The shores of Spy Pond are heavily developed, and the water is now an uncontrolled recreational facility. Inclusion of Spy would require prohibition of all recreational use. Secondly, the simulated operation of the system, which appears in a later chapter (V-H), demonstrated that there would have been few opportunities during a 20-year period when the Pond would have been useful for water conservation purposes. Thirdly, a cursory estimate shows that the economic benefits of the added storage during the 20-year simulation period are greatly exceeded by the costs of construction and operation of the facility, not to mention the economic loss engendered by the elimination of recreation. This too will be demonstrated.

Increased storage in the Hobbs Brook or Stony Brook Reservoirs could be obtained by dredging the bottoms or constructing dikes. In the case of dredging, development of the additional storage would require lowering the invert elevations. In view of the simulation study (Chap. V, para .H) improvement of system operation appears too slight to justify the expense of any increase in storage.

3 Storage Equalization Between Stony & Hobbs

Hobbs Brook Reservoir with a storage capacity of 369 million cubic feet drains a catchment whose area is 6.3 square miles. Stony Brook Reservoir, which stores only 58 million cubic feet drains an area of 17.3 square miles excluding the Hobbs Brook catchment. The respective storage/catchment area ratios are 60.5, and 3.4 million cubic feet/square mile. (This is equivalent to storage capacities of 26 inches and 1.5 inches respectively).

The way to equalize the imbalance between the storages would be to convey to Hobbs Brook Reservoir water that would otherwise spill to the Charles when Stony Brook Reservoir is full. This would require an expensive pumping project to meet a head differential of 100 feet while pumping water in a pressure conduit a distance of about two miles.

The simulation study (Chap. V, par. H) showed that it is possible to operate the system in a manner that would only very rarely (if ever) present the opportunity to save water by pumping in this manner. Consequently, this alternative will be seen to be not justified.

4. Conveyance of Outside Water

There are two feasible sources of outside water. One of these is the MDC connection currently in use. The other is the Sudbury River which drains the adjacent Sudbury watershed to the west. Conveyance of Sudbury water would require four miles of conduit and a pump to meet a head differential of 85 feet. Sudbury water presents a serious coloration problem that would require additional and specialized treatment while the MDC water need not be treated. Therefore it appears that the expense of obtaining the Sudbury water could hardly be justified. The only conceivable reason for developing the Sudbury sources would be to eliminate the necessity of Cambridge to buy MDC water.

5. Develop Wells

The groundwater aquifers underlying the Hobbs Brook subwatershed may be viewed as underground reservoirs with finite storage potential. Groundwater aquifers may be managed in a fashion similar to the management of surface sources. While the groundwater already is indirectly utilized through natural seepage into the reservoirs, additional supplies could be developed with wells. During extended drought periods when Cambridge runs short and MDC experiences heavy demands, wells may be utilized to augment the natural seepage replenishment of the reservoirs.

In order to establish the feasibility of groundwater development, an engineering study based upon detailed information regarding the nature of the subsurface and the manner in which the groundwater currently interacts with reservoir waters would have to be undertaken. Furthermore, careful consideration would have to be given to subsurface riparian rights. Therefore, any recommendations regarding development of this source falls outside of the present study.

6. Sealing of Leaks

A previous study of the Cambridge water system, performed by an independent consultant to the Cambridge Water Department, revealed a potentially serious source of leakage through a highly permeable stratum that connects Stony Brook Reservoir to the Charles River. This leakage could be sealed or tapped by a well. The study was not made available. Therefore, it is not possible to evaluate the utility of any program to salvage this unknown quantity of seepage.

IV. HYDROLOGY

A. Role of Hydrologic Study

Management of water resources begins with a knowledge of the quantity of water that must be managed. Consequently any water resources study must begin with an estimate of surface runoff. Surface runoff is the portion of rainfall that is collected by streams and conveyed to a gaging point or collection point such as a reservoir.

Engineering analysis of proposed projects for system improvement must be based upon a knowledge of the natural inflow to the reservoirs. When the relevant streams are gaged, and records are available over a number of years, a statistical basis for water availability may be established. When such gaging is not immediately available, there are several general approaches to synthesizing the data. One simple way is to assume that the catchment area is similar to one for which gage records are available and to use the ratio of the two catchment areas to transform the known record to an equivalent one for the problem catchment. When the region has no long term records, the hydrologist has recource to other techniques which depend upon records of rainfall rather than runoff.

No direct gaging of the Stony Brook sub-watershed streams is available. The Charles River at Charles River Village is the nearest station for which the required records are available.

B. Cambridge City Records

Fortunately, the excellent operating records kept by the Cambridge Water Department at the Fresh Pond treatment plant provided an indirect but fairly accurate means of estimating the watershed runoff. These records were made available through the courtesy of Mr. William H. McGuiness, Water System Superintendent. The balance of the hydrologic study is contained in the Appendix for this chapter.

V. SIMULATED OPERATION OF THE STONY BROOK SYSTEM

A. Introduction

The purpose of simulating is to gain insight into features of the system that would not otherwise be evident. The results of simulation then become a basis for comparing system alternatives.

The only system alternative simulated here consisted of facilities currently in use. It then became evident that there was no need to simulate the other alternatives.

The data developed in Chapter IV were utilized to simulate 20 years of operation under the projected Cambridge domestic demand. Operating rules were postulated heuristically and are not radically different from the current practice.

Simulation is best performed by a computer. General programs for simulating water resource systems are finding increasing application. In the present study, however, it appeared advantageous to simulate manually. By making reasonable, simplifying assumptions, the computational effort was greatly reduced.

Manual simulation has the advantage of intimacy. The analyst may formulate operating rules by trial and error. The consequences of the rules become immediately evident and the rules may be revised if necessary. The rules finally governing the 20 year simulation were devised in this manner.

The 20 year simulation period included an extended drought (1939-1945) as well as an extended period of water surplus (1954-1958). The features of simulated operation will probably be typical of actual future operation.

B. System Requirements

Three specific water uses are to receive consideration.

1. Meet Cambridge water demands.

These demands must be met through reservoir management, the MDC connection to Cambridge, or a combination of the two. The Cambridge demand used throughout the simulation was derived by taking the actual monthly Cambridge water demands for 1966 and adding a 10% projection. The monthly demand figures used in the simulation are contained in Table III-1. These demand figures are assumed constant from year to year.

2. Provide a recreational pool in Hobbs Brook Reservoir.

Hobbs Brook Reservoir presently has no recreational usage. Inherent in the simulation is the assumption that Hobbs Brook Reservoir will be used for picnicking, sun bathing, and boating (power boats excluded for pollution considerations). In order to have a recreational season during the months of June, July, and August, the storage in Hobbs Brook would have to be maintained at a minimum of one-half, or 185 million cubic feet.

3. Low flow augmentation to the Charles River during the historically dry months of June, July, August, and September.

The present Massachusetts' law allows the MDC to supply a legal maximum of 67 million cubic feet per year for low flow augmentation to the Charles River. However, it is left to the discretion of the MDC in view of its own water storage situation, whether or not it will supply the water for low flow augmentation even when requested by the Public Health Service. The simulation allows for a maximum of 100 million cubic feet per year for low flow augmentation.

C. Physical Components of the System

A schematic representation of the system, as simplified for simulation purposes is presented in Figure V-1.

The monthly runoff data (QHR and QSR) used in the simulation is the same as that derived from the hydrology computer model described in Chapter IV and corresponds to the runoff into Hobbs Brook Reservoirs respectively.

The hydrologic data is complete from 11/1937 to 10/1951 and from 11/1952 to 10/1958 but is incomplete for the water year from 11/1951 to 10/1952. The 20 years of simulation utilizes the computed runoff figures for the periods 11/1937 to 10/1951 and 11/1952 to 10/1958 as if they were continuous.

To simplify calculations the Stony Brook and Fresh Pond Reservoirs were considered to be one reservoir with a storage capacity equal to the sum of their individual storages. The maximum storages of the reservoirs in the System are listed in the following table.

TABLE V-1

Storage Capacities

Reservoir Name	Storage Capacity in Million Cubic Feet	
Hobbs Brook	375[1]	(369)[2]
Stony Brook	54	(54)
Fresh Pond	176	(175)

For the purpose of the simulation the reservoirs were viewed as follows:

Reservoir Name	Storage Capacity in Million Cubic Feet
Hobbs Brook (SHR)	375
Stony Brook and Fresh Pond (SS+F)	230

All water that is collected in the three reservoirs of the Stony Brook system is treated (filtered and disinfected) at a treatment plant shown in the schematic diagram. Water taken from the MDC does not go through the treatment plant but is added to the treated water at a junction below the treatment plant.

[1] Preliminary value at time of simulation study.

[2] Revised value by NED Engineers after study.

D. Historical Observations

Inspection of the historical operating data showed that during the spring runoff months of February, March, April, and May, spillage frequently occurred from Stony Brook Reservoir into the Charles River because (1) Stony Brook was at capacity and the runoff into Stony Brook was not diverted fast enough into Fresh Pond in the event Fresh Pond was not already full or (2) Stony Brook and Fresh Pond were both at capacity.

The historical operating data further indicated that in many months during which spillage occurred there remained unused capacity in the Hobbs Brook Reservoir.

E. Operating Rules

1. Logic

The fact that (1) historically spillage has occurred during the spring runoff even during periods of extended drought and (2) only 40% of the years would provide a surplus of runoff with the projected demand suggested (figure IV-7) an operating rule which would attempt to eliminate or minimize the water wasted as spillage during the spring runoff.

By operating the system so as to keep Hobbs Brook as full as possible and thereby keep Stony Brook and Fresh Pond at lower levels, there would be more excess capacity in Stony Brook and Fresh Pond to store the water that would have ordinarily been spilled when the spring runoff comes. In addition, the probability of maintaining a recreational pool from June through September is maximized.

2. Statement of Rules

With water conservation as the overall objective and with the three system demands (Section B) in mind the following operating rules were formulated:

a. Attempt to start the water year with a storage of 1/3 or more full. (A water year starts November 1 and runs to October 30 of the following year).

b. Meet Cambridge demand every month.

c. When total storage falls below 1/6 of capacity, (1) use MDC water to meet Cambridge demand, and (2) increase the storages in Hobbs Brook and Stony Brook-Fresh Pond Reservoirs by the entirety of their respective runoffs.

d. Maximize the storage in Hobbs Brook Reservoir by letting the total runoff (QHR) into Hobbs Brook accumulate when, (1) Cambridge's water demand can be met by the storage in Stony Brook-Fresh Pond Reservoirs and the runoff into Stony Brook, or (2) another operating rule dictates that Cambridge demand should be met with water supplied by the MDC. (Rule e)

e. Maintain a half depth pool in Hobbs Brook during June, July, and August for recreational purposes.

f. If supplying the Cambridge demand during June, July, and August (when the Stony Brook-Fresh Pond storage has been reduced to between 5 and 20 million cubic feet) would require the storage in Hobbs to be taken below 185 million cubic feet, use MDC water to supply Cambridge.

g. Attempt to supply low flow augmentation according to the following schedule:

TABLE V-2

Maximum Spillage Schedule

Month	Low Flow Augmentation (in million cubic feet/month)
June	15
July	35
August	35
September	15

h. Do not supply low flow augmentation if (a) the water is needed to maintain one-half storage in Hobbs Brook during June, July, and August and (b) the storage in Stony Brook-Fresh Pond during these months has been reduced to between 5 and 20 million cubic feet, combined total.

i. Do not supply low flow augmentation in September if, after meeting the Cambridge demand from Hobbs Brook for September, the total storage of the system would fall below 125 million cubic feet.

The reservoir storages at the end of October 1938 were initialized at one-third capacity. Hobbs Brook was given an initial storage of 125 million cubic feet and Stony Brook-Fresh Pond a storage of 75 million cubic feet.

F. Results of Simulation

1. Sample Computation

Table V-3 of the Appendix for this chapter gives a month by month account of the operating variables. The 20 years of simulated operation began November 1, 1937. The reservoir storages were initialized at the end of October, 1937 at 125 mcf for Hobbs Brook and 75 mcf for Stony Brook-Fresh Pond. The computed runoffs into Hobbs Brook (QHR) and Stony Brook (QSR) for November were 12 and 44 mcf, respectively. The sum of QHR and QSR (in column 5) represents the total input into the system. The demand for November was 94 mcf. The difference of column 5 and column 6 represents the net surplus or deficit for the month. The demand for November 1937 was 38 mcf higher than the runoff supplied and therefore there was a deficit for the month indicated by -38 mcf in column 7. The storage in Hobbs Brook at the end of November was 125 mcf, the same as its initial storage at the end of October. The deficit for the month (38 mcf) was met by reducing the storage in Stony Brook-Fresh Pond to 37 mcf. Therefore, QMDC was 0 mcf and QCS was 94 mcf for the month. QSPS was 0 because the unused storage in the reservoirs was sufficient to trap the runoff. This general procedure was repeated for the remainder of the 20 year period of simulated operation with the different monthly hydrologic inputs and demands.

2. Operation Summary

The following tables provide a summary of the operation:

TABLE V-4

Summary of Operating Data for 20 Year Simulation

		m.c.f.	% of Cambridge Demand
a.	Runoff (QHR and QHS)	24751	108
b.	Cambridge Demand	22880	100
c.	Controlled Spillage	1057	4.6
d.	Uncontrolled Spillage	3771	16.5
e.	MDC Supply	3619	15.8
f.	Runoff minus Uncontrolled Spillage	20980	91.7

TABLE V-5

Summary of Operating Data for 18 Years of Simulation (Flood years 1955 and 1958 excluded)

		m.c.f.	% of Cambridge Demand
a.	Runoff	19199	93.2
b.	Cambridge Demand	20592	100
c.	Controlled Spillage	907	4.4
d.	Uncontrolled Spillage	1124	5.5
e.	MDC Supply	3619	17.6
f.	Runoff minus Uncontrolled Spillage	18075	87.8

Table V-6 shows the yearly controlled and uncontrolled spillages in million cubic feet and the number of months each year that controlled and uncontrolled spillage occurred. Controlled spillage occurs only during the months of June, July, August, and September. Its purpose is low flow augmentation for the Charles River.

TABLE V-6

Simulated Controlled and Uncontrolled Spillages

Year	Controlled Spillage in m. c. f.	# of Months of Controlled Spillage	Uncontrolled Spillage in m. c. f.	# of Months of Uncontrolled Spillage
1938	65	3	0	0
1939	46	2	0	0
1940	50	2	0	0
1941	0	0	0	0
1942	30	2	0	0
1943	59	3	0	0
1944	45	3	0	0
1945	85	3	0	0
1946	100	4	0	0
1947	15	1	0	0
1948	50	2	0	0
1949	30	2	0	0
1950	15	1	0	0
1951	100	4	158	2
1953	67	3	0	0
1954	70	3	52	2
1955	65	4	1131	7
1956	65	3	914	7
1957	15	1	0	0
1958	85	3	1516	3
TOTALS	1057	49	3771	21

Uncontrolled spillage occurs when (1) Stony Brook is at its storage capacity and the runoff into Stony Brook cannot be diverted quickly enough into Fresh Pond in the event Fresh Pond is already full or (2) both Fresh Pond and Stony Brook are at capacity.

Controlled spillage for low flow augmentation (L. F. A.) occurred 49 out of a total possible 80 months. Thus LFA was made available 61.3% of the dry months in which it was desired.

Total runoff was 24751 million cubic feet or 108% of total Cambridge demand. The system appears to be surplus for the twenty years of record. However, 1955 and 1958 were flood years with heavy runoffs, and spillage during these years account for 70%

of the uncontrolled spillage. When total runoff is reduced by uncontrolled spillage, the result represents the amount of useable water. This figure is only 91.7 percent of total Cambridge demand. Figure III-1 shows that runoff exceeded projected Cambridge demand 8 out of the 20 years of simulation. Sixty percent of the years were deficit years, and water had to be brought in from external sources of supply.

The only external source of supply available to Cambridge in the event of a deficit year is the MDC. Table V-7 gives a yearly tabulation of water taken from the MDC to supplement system supply.

TABLE V-7

Simulated MDC Supply

Year	m.c.f.	number of months taken	Year	m.c.f.	number of months taken
1938	0	0	1949	289	2
1939	248	3	1950	297	4
1940	216	3	1951	94	1
1941	473	7	1952	Not included in simulation	
1942	364	6	1953	112	1
1943	206	2	1954	0	0
1944	488	8	1955	0	0
1945	166	2	1956	0	0
1946	50	1	1957	286	4
1947	163	3	1958	0	1
1948	167	2			

During the 20 year period, 3619 million cubic feet of water were drawn from the MDC connection. This represented 15.8% of total Cambridge demand. The range of water taken from the MDC varies from a high of 488 m.c.f in 1944 to a low of 0 in 1938, 1954, 1955, 1956, and 1958. Table V-7 also shows the number of months each year that MDC water was taken. MDC water was taken 52 out of a possible 240 months or 21.7% of the time. The range varied from a high of 8 months during 1944 to 0 months in the years 1938, 1941, 1954, 1955, and 1956.

Operating Rule number e, Section E, specifies that a one-half pool will be maintained in June, July, and August for recreational purposes. This was possible in all but one of the 20 years of simulated operation, the summer of 1941. By May 1941 the spring runoff had only raised Hobbs' storage to 135 million cubic feet making it physically impossible to maintain a minimum recreation pool that year.

G. Results of Historical Operation

Table V-8 summarizes the operating data for the actual historical operation. Juxtaposed are the results of the simulated operation.

TABLE V-8

Historical and Simulated Operating Data Summary

	Historical m.c.f.	Simulation m.c.f.	Simulation-Historical m.c.f
a. Runoff	24751	24751	0
b. Cambridge Demand	16115	22880	6765
c. Uncontrolled Spillage	7690	3771	-3919
d. Controlled Spillage	300	1057	757
e. MDC Water Taken	186	3619	3433

The table indicates the change in the demand characteristics of the system. The demand for the historical operation is 6765 mcf less than the demand for the simulated operation which utilized the projected Cambridge figures. For the 20 years of record, the actual amount of water drawn from the MDC was only 186 mcf or 1.15% of the demand for the period. In view of the historical demand and the drought period during which the MDC water was drawn, the historical operation of the system was usually more than adequate. In the simulated operation, the MDC connection was required to provide 15.8% of the Cambridge demand. These figures clearly point out the system's deficit nature and its future dependence on external sources of supply.

Uncontrolled spillage was 3919 m.c.f. higher in the historical operation. One would expect the uncontrolled spillage figure for the simulated operation to be lower because (1) the projected demand used is higher than the actual demand, (2) the turnover of water in the reservoirs must be greater to meet this increased demand, and (3) increased turnover of water provides increased cumulative storage.

H. Supporting Evidence for Assumptions Made in Chapter III-B

1. Operating Rules

Chapter III-B-1 outlines three basic water usage demands to be met by the Stony Brook System. These are:

a. guarantee Cambridge's demand

b. Maintain a recreational pool at Hobbs during the summer months.

c. Attempt to shift the spillage (if any) of excess water from the spring runoff to the summer months when low flow augmentation is desired. The operating rules developed to meet these demands were specified in detail in Section E of this Chapter.

A review of the simulated operating data indicates that:

a. Cambridge demand was met every month by its own reservoir management, the MDC connection, or a combination of the two; the MDC supplied 15.8% of Cambridge's demand during this period; 872 m.c.f. of controlled spillage used for low flow augmentation could have been used for Cambridge demand.

b. In 19 of the 20 years of simulation, Hobbs Brook maintained storages during the summer months which were sufficient to support recreational activities.

c. Part of the spring runoff could be shifted from the spring to the summer months; 1057 m.c.f. of water was made available by the Stony Brook System for low flow augmentation to the Charles River during the historically dry months of June, July, August and September.

d. Recreation was not competitive with Cambridge demand. Thus, the simulation showed that operating rules could be developed to at least partially satisfy the system's demands.

the MDC at Quabbin Reservoir for Recreational Purposes". The report of the special commission is published in the March 1965 issue of the J. N. E. W. W. A. previously cited. The policy of the commission was that equalizing (treated water) and terminal (water just prior to treatment or distribution) reservoirs should be off limits to any recreational activity. Upstream reservoirs may be utilized with adequate safequards depending upon the classification. Class "A" waters, which are to be utilized without treatment, are prohibited for recreation use. Class "B" waters are those in lightly populated areas requiring treatment and disinfection and may be considered eligible for recreational use. Class "C" refers to polluted water which must be fully treated and is utilized during low flow. Class "C" water may be used at the discretion of the water works superintendent.

4. Application to the Stony Brook System

The Hobbs Brook Reservoir appears eligible for classification as an upstream type, Class "B". Fresh Pond and Stony Brook Reservoirs are apparently terminal and should not be given any further consideration.

With respect to administrative or political implementation of recreation at Hobbs Brook that may develop as a result of subsequent studies, it is germane to cite the position of the American Water Works Association. "The American Water Works Association registers its opposition to legislation permitting or requiring the opening of domestic water supply reservoirs and adjacent lands to recreational use. Control of water supply reservoirs must remain the prerogative of the water purveyor".

5. Use of Hobbs for Recreation Only

A possible system alternative not previously considered would consist of reserving Hobbs Brook Reservoir exclusively for recreation. If Stony Brook Reservoir was to continue to collect watershed runoff for domestic supply, the Hobbs Brook outflow would have to be diverted around Stony Brook Reservoir. Otherwise, Cambridge would have to depend exclusively upon the MDC for its water.

Loss of Hobbs Brook Reservoir would decrease water availability to Cambridge by approximately 25%, and possibly more. This would involve an annual cost to the system of about $250,000 additional storage could hardly be justified by the cost of providing the additional storage. In the case of Spy Pond such expenses include pumping, piping, and loss of recreation.

A similar analysis could be applied to the proposal to increase the storage of reservoirs already in the system through dredging or adding to the surface area, and a similar conclusion reached.

3. Storage Equalization Between Stony and Hobbs

The logic which justifies the proposal of storage equalization between Stony and Hobbs by pumping is elaborated in Chapter III-B-3. For pumping to have any utility at all these three conditions would have to exist: (1) Stony Brook and Fresh Pond would be at capacity, (2) Hobbs Brook would have excess capacity, (3) the flow from Hobbs Brook to Stony Brook would be minimal if not zero. If all three conditions existed, there would be utility in pumping water from Stony to Hobbs to utilize the excess storage in Hobbs.

However, the simulation study showed that operating rules could be devised so that whenever uncontrolled spillage occurred, Hobbs Brook would be at capacity. (Table V-3 in the Appendix gives proof of this statement). Therefore the simulated operating data indicates that the system can be operated in a manner which would completely eliminate the need for storage equalization by pumping.

It is noted that all possible runoff situations have not been explored in the sample 20 years of simulation. It may very well be possible to devise a situation where storage equalization between Stony and Hobbs Brook by pumping could occasionally be utilized and water thereby conserved. However, it is highly doubtful whether the value of the water conserved could justify the expense of installing and maintaining pumping facilities.

4. Sources of Outside Water

The Sudbury River is a potential source of outside water. But as pointed out in Chapter III-B-4 the only conceivable reason for development of the Sudbury source would be to eliminate the necessity for Cambridge to buy MDC water. The expense involved in installing pumping facilities between the Sudbury River and the Stony Brook System cannot be justified as long as the MDC connection is in operation.

Water pumped from the Sudbury River into Hobbs Brook Reservoir could be used for low flow augmentation to the Charles River during the summer months. However, the MDC already serves this purpose. As long as the MDC connection is capable of meeting the Cambridge water deficit, another outside source of supply is beyond serious consideration.

I. Limitations of Simulation

A simulation based upon a monthly water budget does not reflect the details of daily operation. It is possible that certain monthly figures would have to be altered as a result of special situations encountered on certain days. Inspection of the daily records, however, did not indicate that the major features of the monthly simulation would be seriously impaired.

The operating rules required that Hobbs be closed during the spring runoff season in order to allow collection of a recreational pool while Stony and Fresh were utilized for supply purposes. This usually meant that Stony and Fresh were kept quite low to allow conservation of water that would otherwise spill. There may be valid reasons for operating these two reservoirs at higher levels than suggested by the simulation. This would detract from the system's ability to conserve water and would increase uncontrolled spillage.

It is not the purpose of this report to recommend that Cambridge alter its present mode of operation. The simulation was presented merely to demonstrate the feasibility of a particular operation in the light of the inflow record and the projected demands. A careful study of the system operation with a view to developing practical operating rules would require a computer formulation capable of analyzing the daily situation and perhaps even the hourly situation. In addition, such a study would require the close coordination of the system analyst with the water system superintendent to insure that all practical contingencies were given due consideration.

VI. ECONOMIC EVALUATION OF IMPROVEMENT PROPOSALS

A. Introduction

Chapter V-H discusses the various proposals for improving the Stony Brook Water Resources System from a water budget standpoint. The water budget analysis constitutes evidence for the infeasibility of improving the system through additional storage, storage equalization between Hobbs Brook and Stony Brook, and the conveyance of outside water other than MDC. With such evidence one could conceivably dismiss these proposals. However, further insight into the Stony Brook System may be gained by examining the economic consequences of these proposals.

B. The Value of Water in the System

If Cambridge cannot meet its water demands, the supply must be augmented with MDC water. The cost of MDC water supplied to Cambridge is $900 per million cubic feet. It seems logical therefore to assign a value of $900/m. c. f. for all water in the system which can be made available to service the Cambridge demand.

A distinction should be made between water in the system which can be used to meet the Cambridge demand and water used for low flow augmentation which can be used only for that purpose. In the 20 years of simulated operation the Stony Brook System provided 1057 m. c. f. of controlled spillage for low flow augmentation to the Charles River during the dry summer months. In all but two of the years water that was utilized for low flow augmentation could have been used to meet the Cambridge demand in the near future. But in 1954 and 1955, 185 m. c f. of water used for low flow augmentation could not have been conserved to meet the Cambridge demand at a later date because the heavy runoff in those years filled the reservoirs. (See Table V-3). For the purpose of the economic analysis to follow, water that could be used only for low flow augmentation will be given a value of $75 per m. c. f. This is the nominal fee charged by the MDC to provide water for low flow augmentation.

C. Value of Recreation

The operating rules for the simulation specify that Hobbs Brook be maintained at a one-half pool for recreational purposes during June, July, and August. It is noted that the simulation study should in no way be taken as a recommendation to use Hobbs Brook for recreational purposes. However, the simulation does attempt to prove or disprove the feasibility of maintaining adequate storage in Hobbs Brook during the summer months for recreational useage, and allows an estimate of the economic value.

Planners for the Corps of Engineers estimate a value of $3000/acre of water surface made available for recreational purposes.

This valuation is based upon the economic concept of replacement cost and is to be amortized over a 30 year period at 3 1/8% interest per year.

The surface area of Hobbs Brook is 558 acres. Therefore, at $3000 per acre the total 30 years recreational value of Hobbs Brook is $1,674,000. This can be translated to an annual benefit of $88,000. (30 years at 3 1/8%).

D. Value of Improvement Proposals

1. Operating Rules

The first suggestion for improving the system in Chapter III-B was the development of operating rules within the framework of the existing system. This is precisely what the simulation did. During the 20 years of simulated operation there were 20,980 m c.f of water which could have been used to meet the system's demands. This figure represents the difference between total runoff and uncontrolled spillage. Of this 20,980 m.c.f., 20,795 m.c.f could have been used to meet the Cambridge demand and the remaining 185 m.c.f., defined as surplus, could have been used for low flow augmentation. The annual average of water available for supply and surplus are thus, 1035, and 9 m.c.f., respectively. Table VI-I assigns values to these quantities of water according to the conventions adopted in Sections B and C.

TABLE VI-I

Annual Valuation of Stony Brook System With Simulation Operating Rules and No Engineering Improvements

Water Use Classification	Quantity (m.c.f.)	Valued At $/m.c.f.	Total Value
a. Cambridge demand	1035	$900	$931,500
b. Low Flow Augmentation	9	75	675
c. Recreation	558 acres	88,000/ 558 acres	88,000
d. Total Annual Valuation			$1,020,175

This figure represents the average annual worth of water in the Stony Brook System, during the twenty years of simulated operation.

2. Value of Additional Storage

Chapter V-H-2 assumes that 150 m. c. f. of additional on line storage could be added to the Stony Brook System by connecting an existing reservoir, namely Spy Pond, to the system. Analysis of the simulated operating data in Table V-9 showed that an additional 412 million cubic feet of water could have been conserved to help supply the Cambridge demand over the 20 year period as a consequence of the added storage. This water has a value of $900 per m. c. f. in accordance with Section B. The average annual value of this water is 20. 6 m. c. f. per year times $900 per m. c. f. or $18, 540. For such a proposal to be feasible the annual expense of installing and operating pumping facilities would have to be less than $18, 540. Loss of recreation at Spy Pond would also have to be considered. It is highly unlikely that the average annual cost of installing the pumping facilities would be less than $18, 540 a year, let alone the operating expenses, and therefore this proposal can be discounted as uneconomic.

Providing additional storage by dredging or adding to the surface area of existing reservoirs would be an even more expensive proposition.

3. Value of Storage Equalization Between Stony and Hobbs

Examination of the simulated operating data in Chapter V-H-3 showed that during the 20 years of simulation it was possible to operate the system so that there would be no utility whatsoever in pumping water from Hobbs Brook to Stony Brook. Therefore, the storage equalization proposal would add nothing to the total annual evaluation calculated in Table VI-I. In fact the valuation would have to be decreased by the cost of installing and maintaining pumping facilities.

4. Value of Conveyance of Outside Water

The undesirability of conveyance of outside water (as described in Chapter III-B-4) can be immediately demonstrated. In order to make water from the Sudbury River available for Cambridge use, pumping facilities would have to be installed, and the water would have to be treated. Cambridge can presently buy water from the MDC which requires no treatment and no installation of pumping facilities.

E. Conclusion

The operation of the Stony Brook System under existing conditions and in accordance with the operating rules described in the simulation chapter would yield a higher valuation than operating the system with the three postulated engineering improvements (i. e. additional storage, storage equalization or conveyance of outside water other than MDC).

VII. POLITICAL AND ADMINISTRATIVE CONSIDERATIONS

A. Recreation

1. The Controversy

Although it has been demonstrated that a recreational pool may be maintained in the Hobbs Brook Reservoir 19 years out of 20 and that considerable economic utility may be attached to recreational use, any recommendation that Hobbs Brook Reservoir actually be utilized for recreation has been carefully avoided. Recreational use of water supply reservoirs is a controversial issue. Legitimate arguments, pro and con, have been made by responsible parties. The March 1965 issue of the "Journal of the New England Water Works Association" is devoted to the problem.

It does not appear appropriate to express an attitude in this report supporting either point of view. However, it is important to expose the issues so that the work may contribute to the best planning decisions.

2. A Case Against Recreation

The following people have gone on record (in the aforementioned journal) as solidly opposed to combined water supply and limited recreational use of surface waters:

a.	Harold J. Toole	Director of Water Division, Met. District Comm., Boston, Mass.
b.	Clarence L. Ahlgren	Chief Engineer, Manchester Water Works, Manchester, New Hampshire
c.	Peter C. Karalekus	Chief Engineer, City of Springfield, Massachusetts
d.	John P. Lynch	Chemist, City of Springfield, Mass.
e.	Alexander J. Martin	Deputy Mgr. for Supply & Purification, The Water Bureau, Met. District,
f.	X. H. Goodnough	Director & Chief Engr, Dept. of San. Engrg, Mass. State Dept. of Public Health

Evidence has been presented that even the most limited form of recreational use may generate severe pollutional problems. Karalekus and Minkus cite increased coliform bacteria counts attributed solely to fishing activity. In addition, the authors cited describe other problems encountered and indicate that the public cannot be relied upon to conform to reasonable regulations governing the limited recreational use of a water supply reservoir.

The cited authors are considered authorities on the maintenance of water supply and distribution systems. Their opinions are based upon years of operating experience. As guardians of the public health, they are forced to take a position which maximizes their ability to provide safe water with a minimum of risk. Consequently, they maintain a somewhat more conservative posture than any other water use advocate.

3. A Case for Limited Recreation

In an urban region the pressure to open recreational areas for public use is considerable. The citizen not only demands optimal quality drinking water, but requires areas of rest and relaxation where he may stroll in a pastoral setting, sailboat, fish, swim or otherwise temporarily escape from the city. Competition for use of surface waters in densely populated regions is intense. When all available local ponds and lakes have been utilized for recreation and the demand for such activity continues to exceed the supply, pressure is put upon authorities to open water supply reservoirs for limited recreational use.

The Institute of Water Engineers (London, England) have established a code of practice with respect to limited recreational development of water supply reservoirs. The code and supportive material is published in the March 1965 issue of the "Journal of the New England Water Works Association". The following quotation comes from the "Final Report of the Council on the Recreational Use of Waterworks": "Where water is filtered and sterilized, it should be possible to allow the public to enjoy whatever recreational facilities can be provided".

The Commonwealth of Massachusetts established a "Special Commission" to "investigate and study relative to the advisability of using all or part of the land and waters under the control of the MDC at Quabbin Reservoir for Recreational Purposes". The report of the special commission is published in the March 1965 issue of the J. N. E. W. W. A. previously cited. The policy of the commission was that equalizing (treated water) and terminal (water just prior to treatment or distribution) reservoirs should be off limits to any recreational activity. Upstream reservoirs may be utilized with adequate safequards depending upon the classification. Class "A" waters, which are to be utilized without treatment, are prohibited for recreation use. Class "B" waters are those in lightly populated areas requiring treatment and disinfection and may be considered eligible for recreational use. Class "C" refers to polluted water which must be fully treated and is utilized during low flow. Class "C" water may be used at the discretion of the water works superintendent.

4. Application to the Stony Brook System

The Hobbs Brook Reservoir appears eligible for classification as an upstream type, Class "B". Fresh Pond and Stony Brook Reservoirs are apparently terminal and should not be given any further consideration.

With respect to administrative or political implementation of recreation at Hobbs Brook that may develop as a result of subsequent studies, it is germane to cite the position of the American Water Works Association. "The American Water Works Association registers its opposition to legislation permitting or requiring the opening of domestic water supply reservoirs and adjacent lands to recreational use. Control of water supply reservoirs must remain the prerogative of the water purveyor".

5. Use of Hobbs for Recreation Only

A possible system alternative not previously considered would consist of reserving Hobbs Brook Reservoir exclusively for recreation. If Stony Brook Reservoir was to continue to collect watershed runoff for domestic supply, the Hobbs Brook outflow would have to be diverted around Stony Brook Reservoir. Otherwise, Cambridge would have to depend exclusively upon the MDC for its water.

Loss of Hobbs Brook Reservoir would decrease water availability to Cambridge by approximately 25%, and possibly more. This would involve an annual cost to the system of about $250,000 plus the cost of a diversion. In view of an annual recreational benefit estimated at $88,000 per year, this alternative hardly appears justified. Even if one were to double the annual recreation benefit by allowing unlimited recreational use, the alternative would not appear attractive.

Of course, Cambridge could be supplied completely by MDC, and the entire reservoir system could be developed for unlimited recreation. One would then have to justify an annual recreational benefit of at least $1,000,000.

Even if recreational economic benefits were competitive, neither of the proposals can be considered attractive. Either one would require a compensation to the City of Cambridge. In view of the fact that Cambridge citizens consider themselves fortunate in enjoying a quality of drinking water superior to the MDC untreated supply and at a lower unit cost, the cost of compensation is likely to be high. In fact one may anticipate vigorous opposition to any proposal requiring the City to relinquish a system considered quite satisfactory at any level of compensation.

From a water availability standpoint on a regional basis, the Northeastern United States may continue to anticipate periods in which water will be in short supply. A common sense systems principle would be to conserve local sources of domestic water supply in order to minimize the demand upon remote sources. The MDC source is the Quabbin Reservoir in Western Massachusetts which is part of the Connecticut River System. During the recent Northeast drought, the MDC source was seriously depleted.

While the MDC welcomes the opportunity to supply cities and towns in the district defined by the legislation creating their authority, they recognize the desirability of encouraging continued utilization of local sources of water. For this reason, Cambridge and several other towns enjoy a contractual relationship to the MDC enabling them to augment local sources.

It thus appears that exclusive utilization of Hobbs Brook Reservoir for recreation cannot be justified on three counts:

a. There is no apparent economic advantage.

b. It would be difficult to accomplish politically.

c. It appears undesirable from the standpoint of regional water supply capability.

6. Summary

The answer to the question of the desirability of limited recreational development of Hobbs Brook Reservoir is outside the scope of this report. The problem should be considered in the context of the greater Charles River Basin Watershed and the Boston metropolitan area. A sound decision with respect to combined usage should be documented by a demonstration that the course of action selected is in the best interests of the public.

B. Low Flow Augmentation

During most years the simulation demonstrated that water programmed for low flow augmentation had to be purchased by Cambridge from the MDC later during the same water year or the following year. Consequently, the water could not usually be considered surplus. Unfortunately, one cannot determine in advance whether water is surplus or not. It depends upon future inflows. Therefore if the Stony Brook System were to attempt to meet a portion of the Charles River low flow augmentation requirements in a given water year, there is a definite probability that the water released will not have been surplus. This probability is approximately 80%. In order to take advantage of the 20% probability that the system has surplus water in any year, one would have to guarantee to Cambridge a quantity of water from the MDC without charge in the event that water released for low flow would later prove not to have been surplus.

This concept of system regulation is not currently consistent with legislation regulating the relationship of the MDC to independent systems. While conceptually it is worth introducing the notion of a compensatory relationship, it would require a change of legislation to bring this about. In the case of the Stony Brook System, the amount of surplus water and the probability of its availability are too small to warrant further study of the compensation concept. A better case may perhaps be made with respect to other sub-basins in the Charles River Study.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. Pertinent to the Hobbs Brook Sub-watershed

1. Present utilization of the water resources of the Hobbs Brook sub-watershed is satisfactory and should be continued. The major use is water supply to the City of Cambridge.

2. Owing to zoning regulations and planning policies of the Towns of Lincoln and Weston, the major part of the watershed area does not appear threatened by the regional trend toward urbanization. In addition, the projected water utilization of Lincoln and Weston does not pose a problem of serious competition with Cambridge for the Hobbs Brook system runoff.

3. The present system is considered deficit in that demand exceeds supply in a given water year with a probability of 62.5%. Therefore, an outside source of water will be required.

4. The MDC currently supplies the system with water upon demand. The arrangement appears satisfactory to the two contractual parties, the MDC and the Cambridge Water Department. Therefore, it is recommended that other potential outside sources not be developed.

5. Limited recreational use of Hobbs Brook Reservoir is feasible. The question of recreational use of water supply reservoirs is controversial. A satisfactory administrative and legal arrangement must be formulated in advance of any recreational development. Such arrangements would have to guarantee the quality of the water.

6. The Stony Brook System may be operated in a manner which occasionally makes surplus water available for low flow augmentation to the Charles River. However, in view of the risk that controlled spillage may not be surplus (i.e. inadequate runoff occurs in the following water year) administrative and legal arrangements would be required to guarantee compensation to Cambridge. The MDC does not currently recognize this form of compensation.

7. The cost of additional storage to the system which could be achieved by adding a reservoir (i.e. Spy Pond) or increasing the size of existing reservoirs through excavation cannot be justified.

8. The cost of a pumping station and pipe system to convey water from Stony Brook to Hobbs Brook Reservoirs cannot be justified. In fact, it appears that this proposal has no utility whatsoever.

9. The cost of conveyance of water from the Sudbury River cannot be justified in view of the availability of MDC water and the added treatment required for Sudbury River water.

10. From an economic viewpoint the only feasible source of additional water (other than MDC) would be a well or wells in the watershed area. This source would have to be proved by an independent study based upon a detailed groundwater survey.

B. Pertinent to Analysis of Water Resource Systems

1. The disciplines of engineering systems analysis have contributed to the study through:

a. Development of the hydrology which became the basis of the simulation study.

b. Design and execution of a 20 year simulation of system operation which constituted the major documentation of the study.

2. The analytical principles introduced herein may be applied to other sub-systems of the Charles River System.

3. Simulation of system operation is a valuable tool. It constitutes the most significant basis for an economic analysis of system alternatives.

4. The ability of the electronic computer to process vast quantities of information has been utilized to compute the system hydrology. Future studies should extend computer application to the task of simulating system operation and estimating economic benefits of system alternatives.

ACKNOWLEDGEMENTS AND IDENTIFICATION OF PERSONNEL

1. The preparation of this report was administered by:

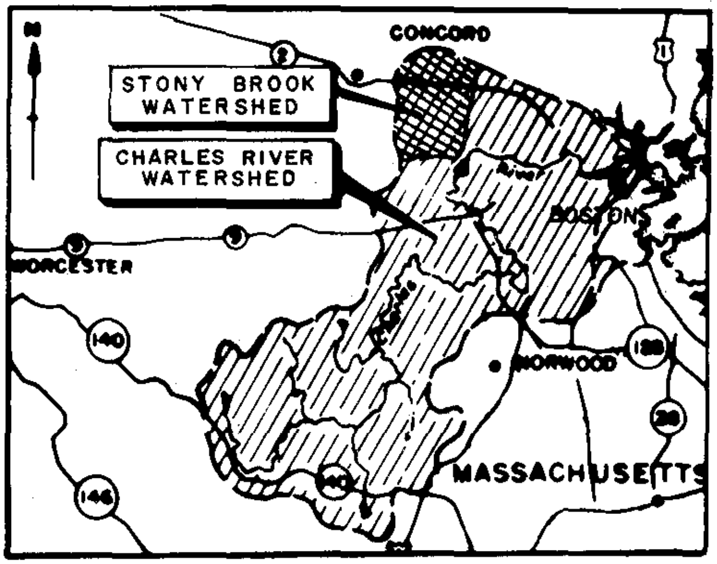
   a. Colonel Remi O. Renier, USA, Division Engineer
   b. John Wm. Leslie, Chief, Engineering Division
   c. Edward L. Hill, Chief, Planning Branch
   d. Joseph L. Ignazio, Chief, Basin Planning Section
   e. John M. Lind, Project Engineer, Charles River Watershed Study

2. This report was prepared under the direction of Frederic March, Graduate Student, Department of Civil Engineering, M. I. T., and Corps of Engineers Graduate Associate.

3. John St. Peter, Graduate Student, Sloan School of Management, M. I. T., and temporarily with the Corps of Engineers, rendered invaluable assistance and prepared Chapters V and VI of this report.

4. William H. McGuiness, Superintendent of the Water Department, Cambridge, Massachusetts, provided thirty years of operating data which became the basis of Chapter IV. In addition, Mr. McGuiness donated valuable time in discussing various practical problems connected with operating a water supply system, and made many helpful suggestions.

5. Other people who contributed information and helpful discussion include Mr. Charles O. Clark of the Metropolitan District Commission. Personnel employed by the Towns of Lincoln, Weston, and Waltham were consulted in the course of the study.

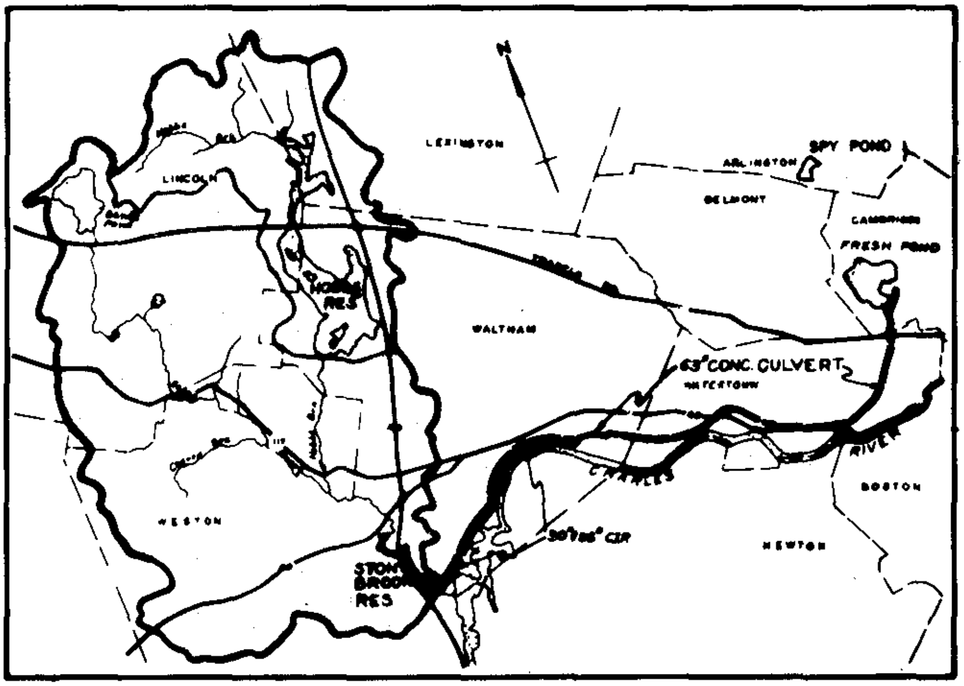


LOCATION MAP

SCALE IN MILES

10 0 10

FIGURE II - 1



VICINITY MAP

SCALE IN MILES

0 1 2 3

FIGURE II - 2

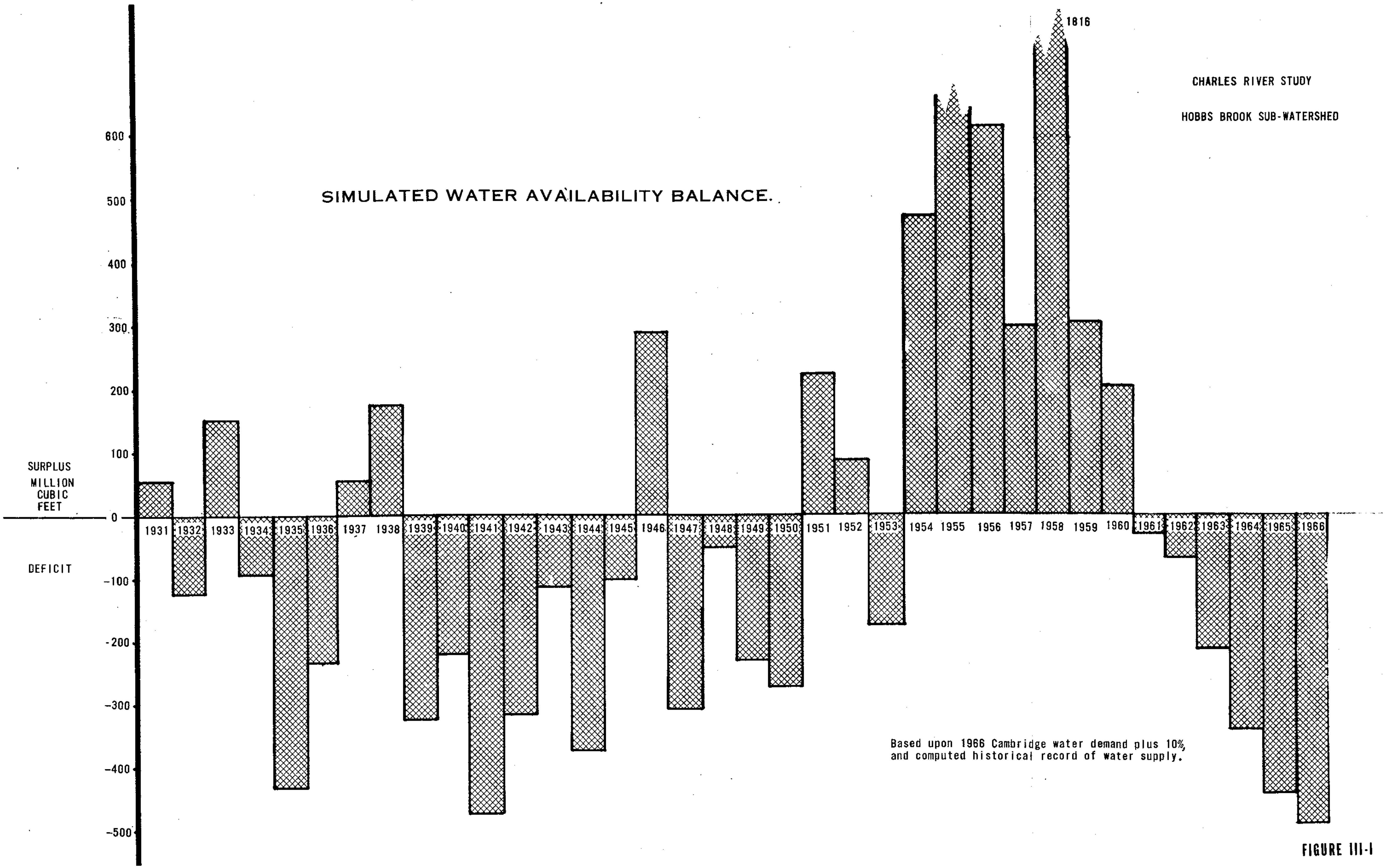
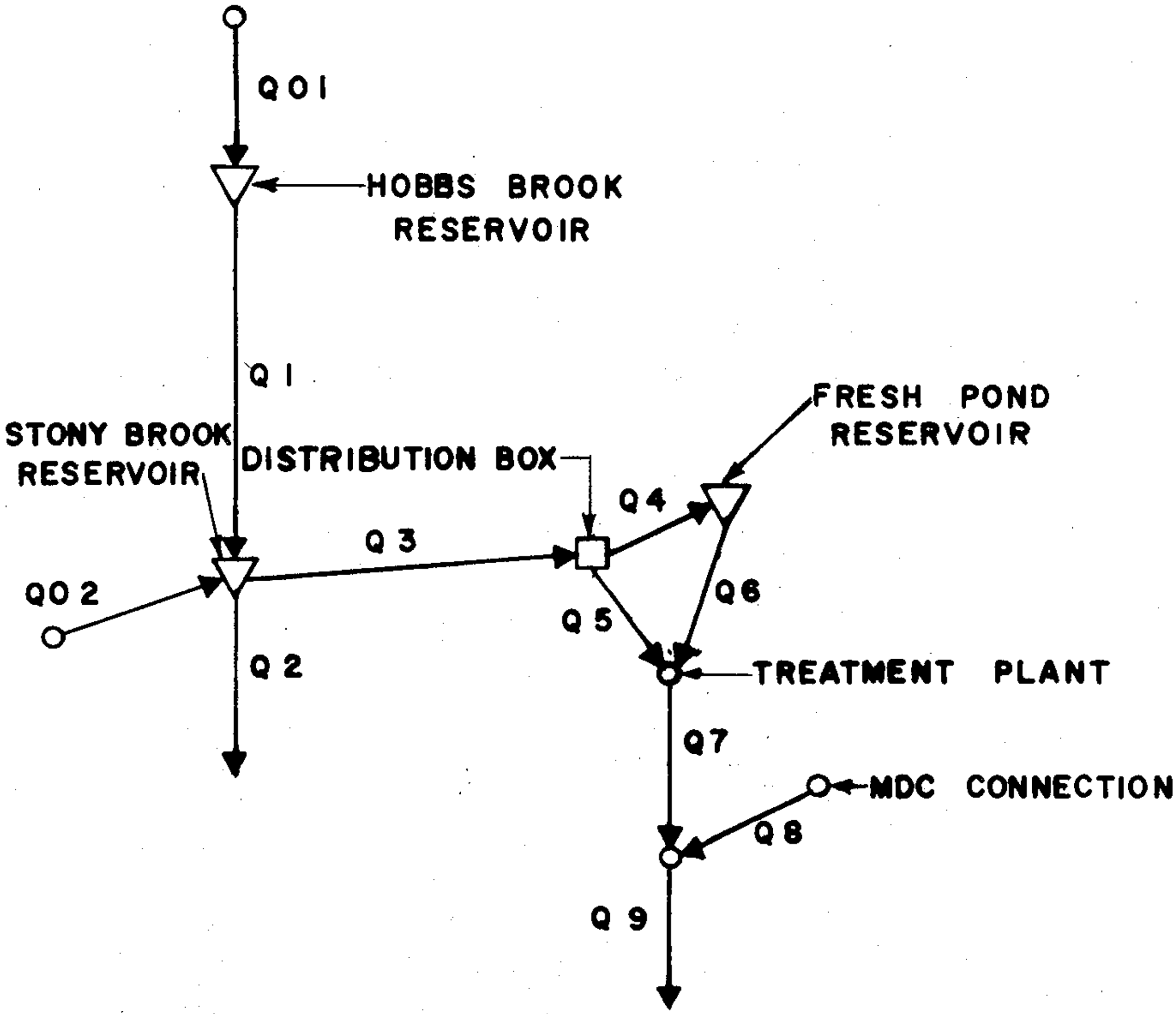

CHARLES RIVER STUDY
HOBBS BROOK SUB-WATERSHED
SIMULATED WATER AVAILABILITY BALANCE.
SURPLUS
MILLION CUBIC FEET
DEFICIT
600
500
400
300
200
100
0
-100
-200
-300
-400
-500
1816
1931 1932 1933 1934 1935 1936 1937 1938 1939 1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950 1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966
Based upon 1966 Cambridge water demand plus 10%, and computed historical record of water supply.

FIGURE III-I



SCHEMATIC FOR HYDROLOGY

FIGURE IV-I

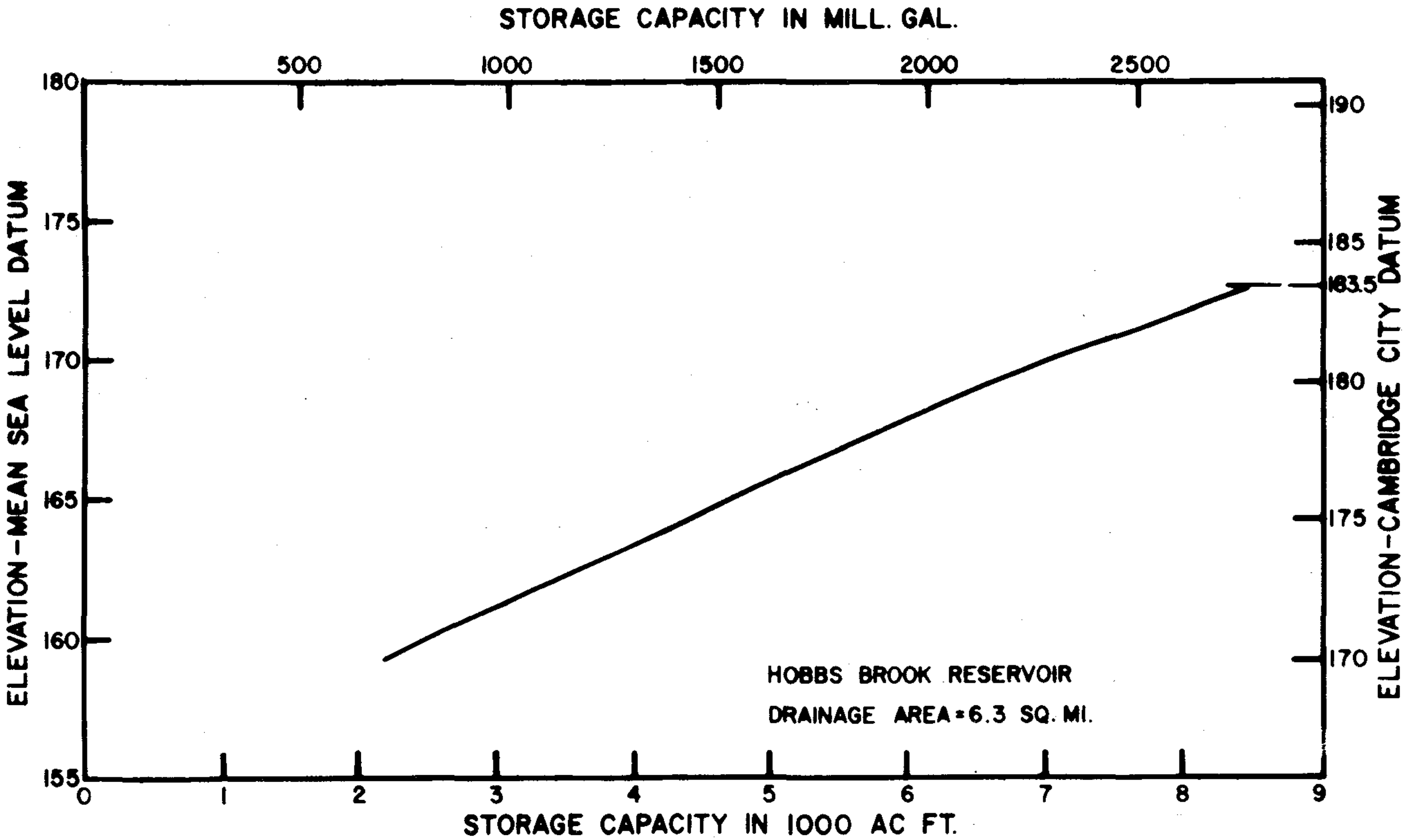

STORAGE CAPACITY IN MILL. GAL.
500
1000
1500
2000
2500
180
175
170
165
160
155
190
185
183.5
180
175
170
ELEVATION-MEAN SEA LEVEL DATUM
ELEVATION-CAMBRIDGE CITY DATUM
HOBBS BROOK RESERVOIR
DRAINAGE AREA = 6.3 SQ. MI.
0
1
2
3
4
5
6
7
8
9
STORAGE CAPACITY IN 1000 AC FT.

FIGURE IV-2

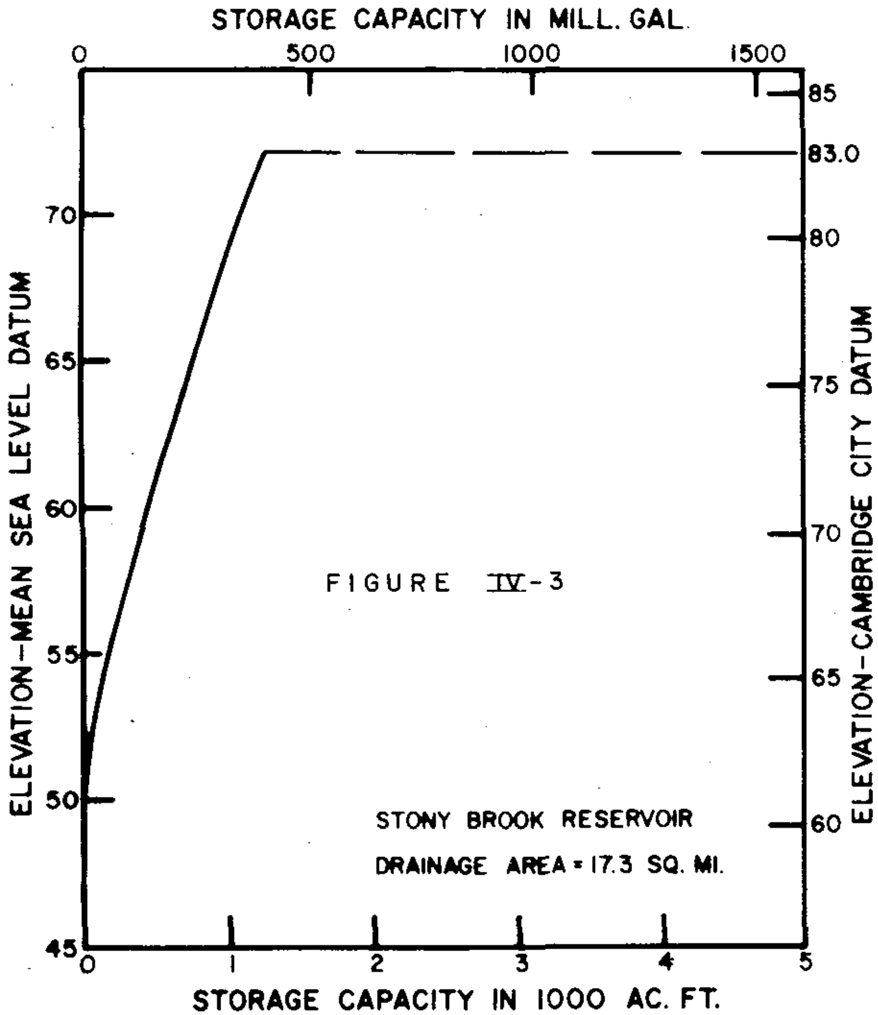


FIGURE IV-3

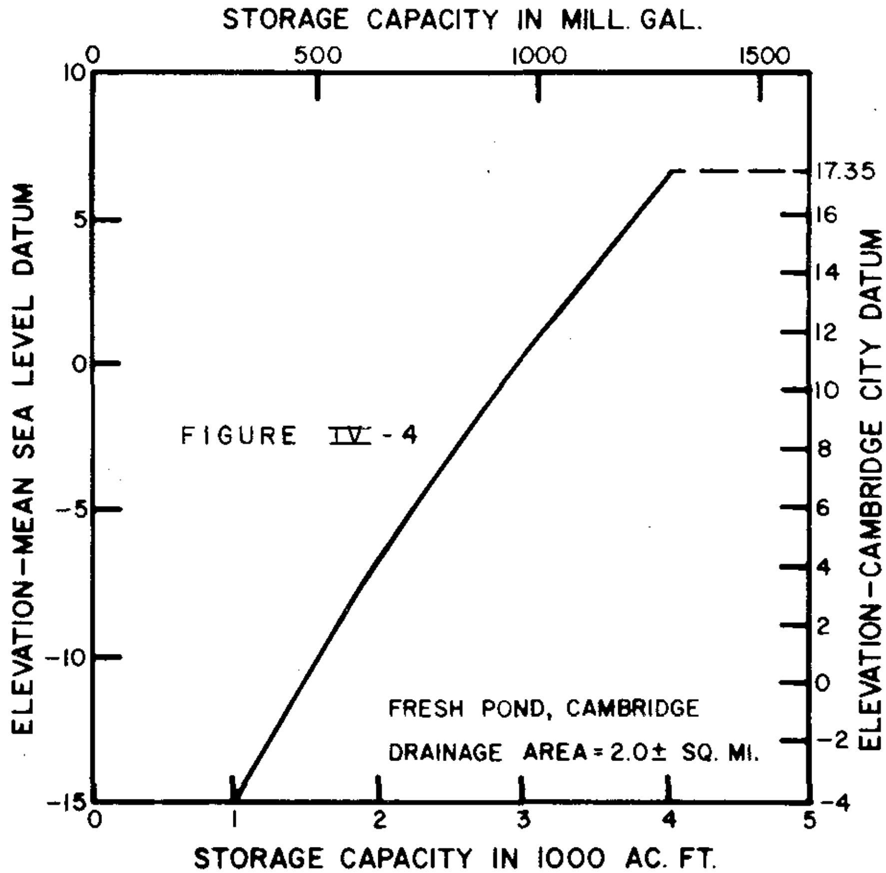


FIGURE IV-4

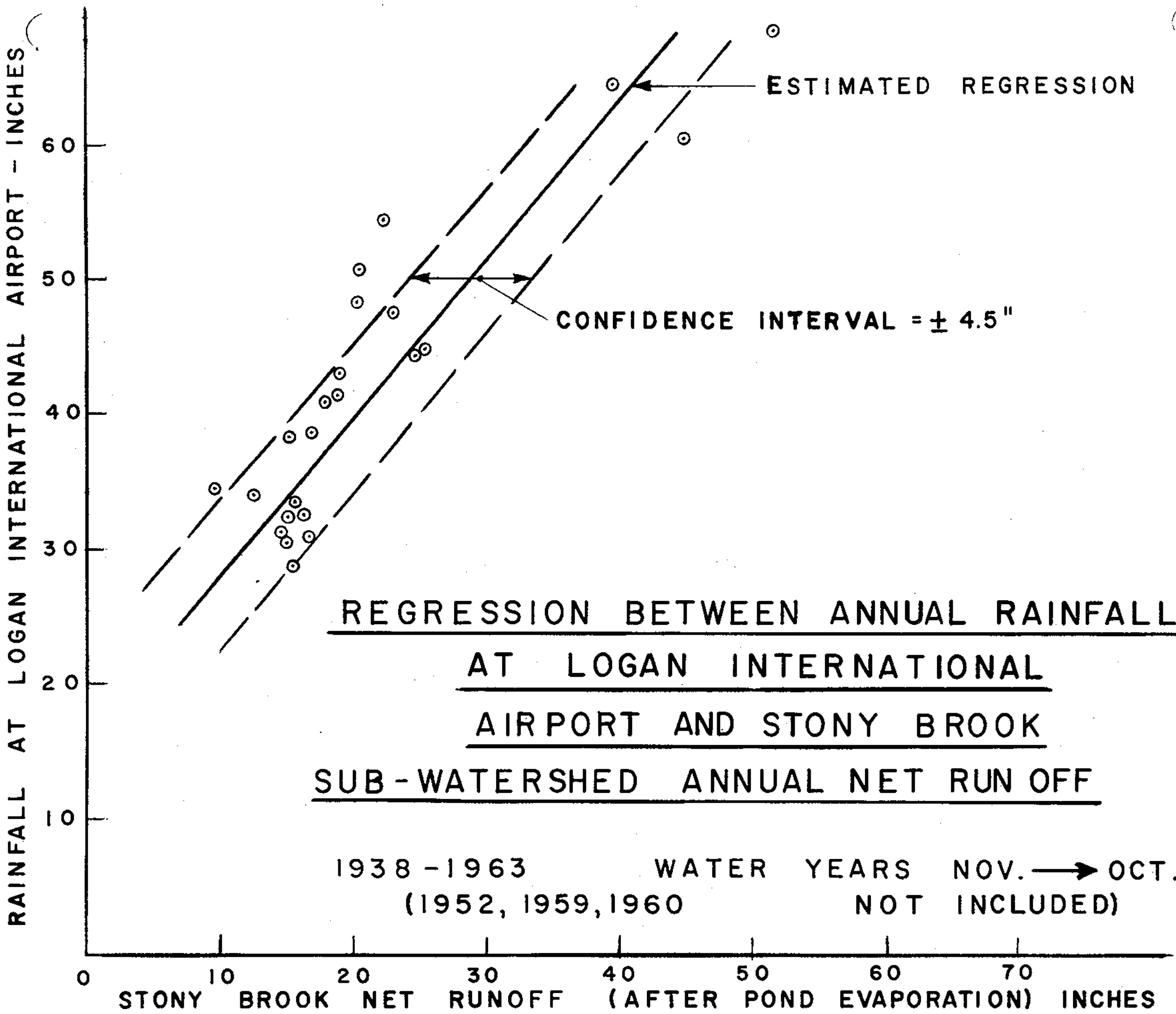

RAINFALL AT LOGAN INTERNATIONAL AIRPORT - INCHES
10
20
30
40
50
60
ESTIMATED REGRESSION
CONFIDENCE INTERVAL = ± 4.5"
REGRESSION BETWEEN ANNUAL RAINFALL AT LOGAN INTERNATIONAL AIRPORT AND STONY BROOK SUB-WATERSHED ANNUAL NET RUN OFF
1938 - 1963 WATER YEARS NOV. → OCT.
(1952, 1959, 1960 NOT INCLUDED)
0
10
20
30
40
50
60
70
STONY BROOK NET RUNOFF (AFTER POND EVAPORATION) INCHES

FIGURE IV - 5

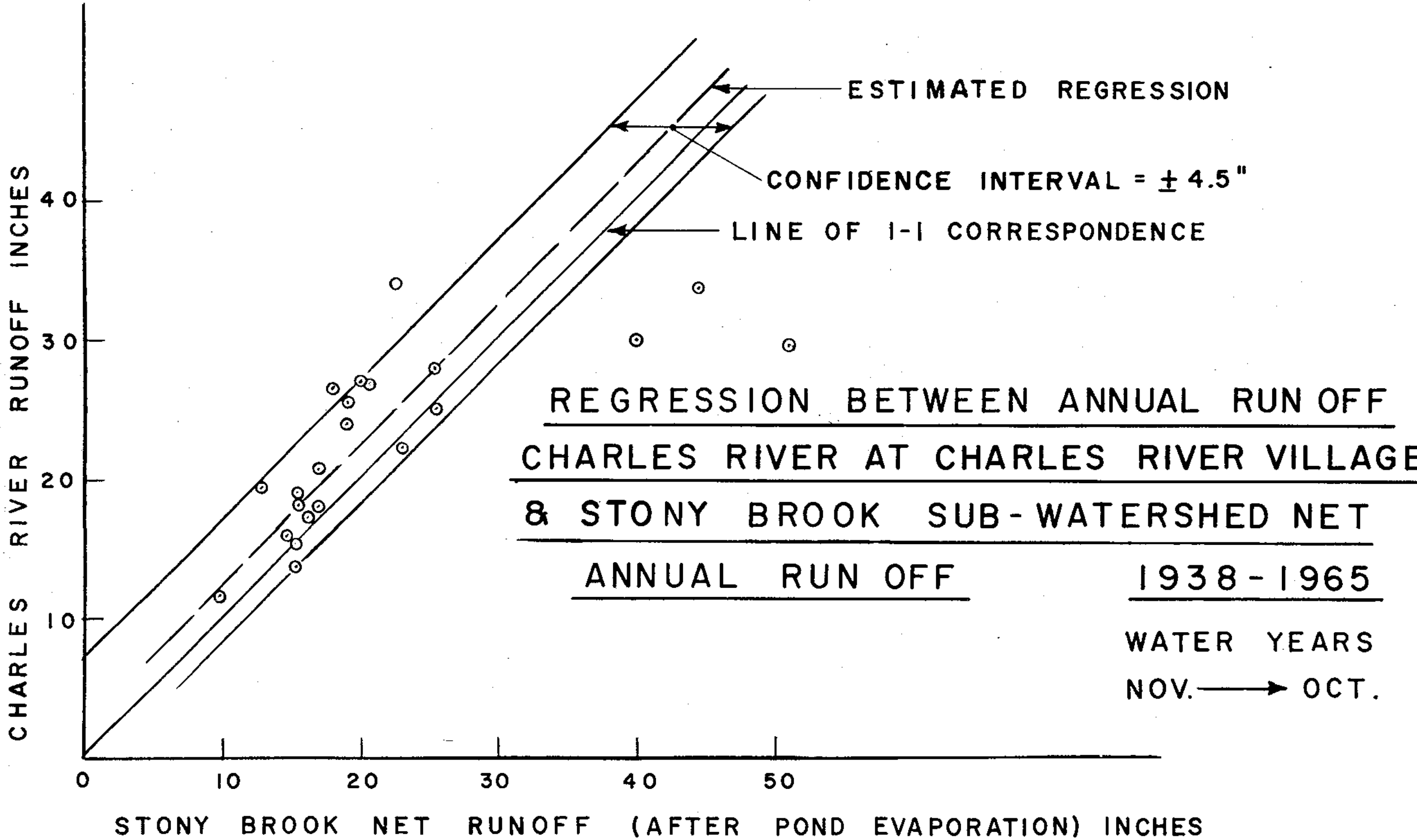
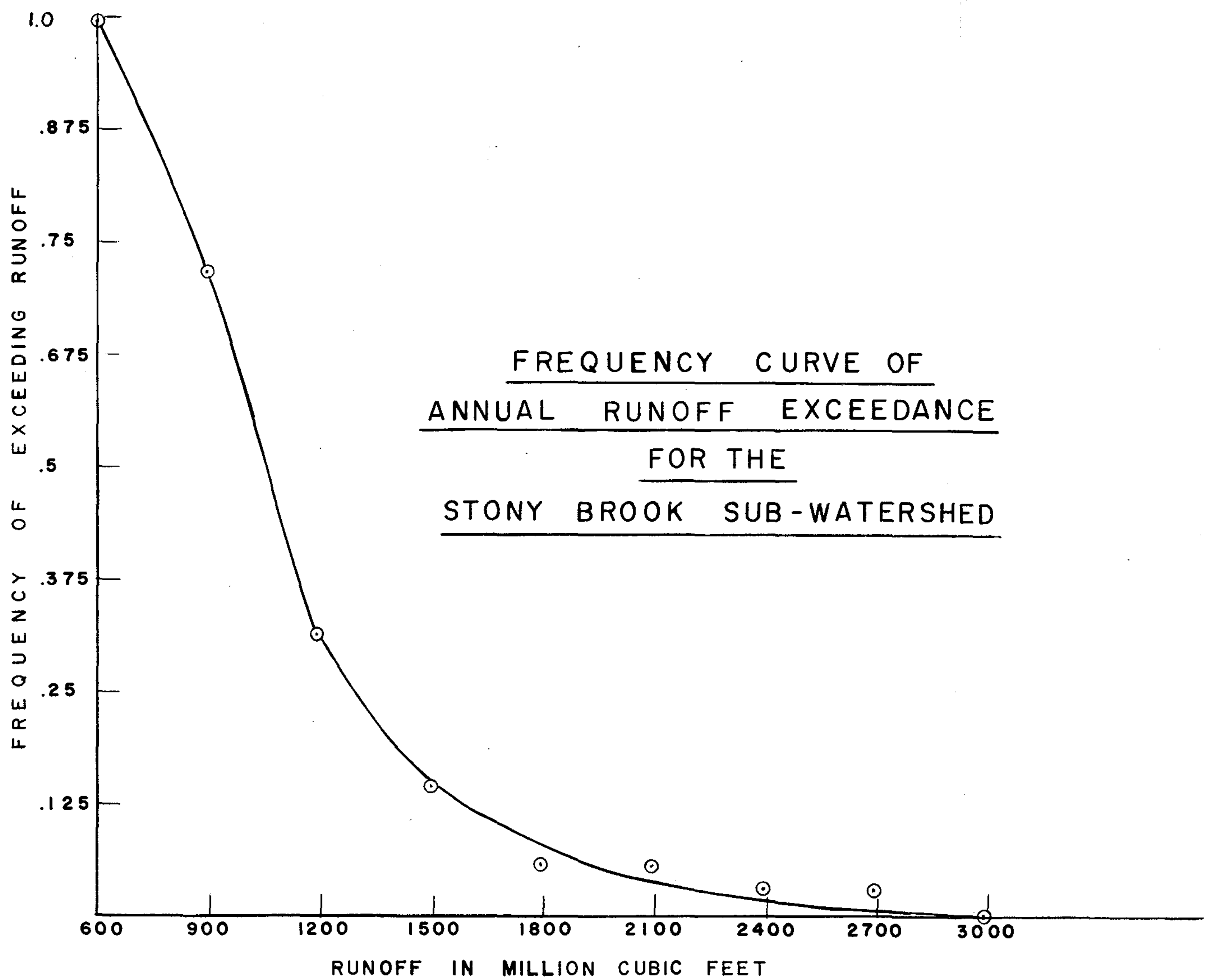
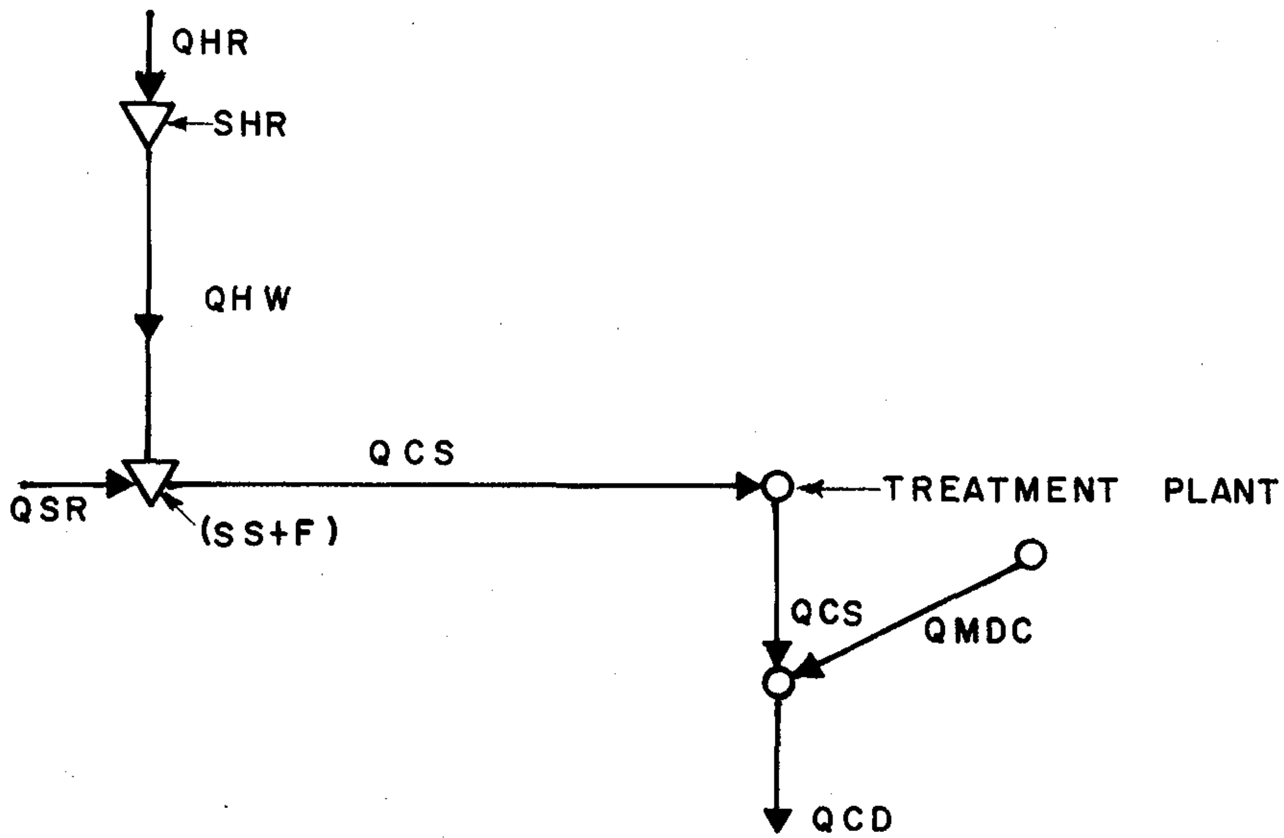

ESTIMATED REGRESSION
CONFIDENCE INTERVAL = ± 4.5"
LINE OF 1-1 CORRESPONDENCE
REGRESSION BETWEEN ANNUAL RUN OFF
CHARLES RIVER AT CHARLES RIVER VILLAGE
& STONY BROOK SUB-WATERSHED NET
ANNUAL RUN OFF 1938-1965
WATER YEARS
NOV. → OCT.
CHARLES RIVER RUNOFF INCHES
10
20
30
40
0
10
20
30
40
50
STONY BROOK NET RUNOFF (AFTER POND EVAPORATION) INCHES

FIGURE IV 6



FREQUENCY CURVE OF
ANNUAL RUNOFF EXCEEDANCE
FOR THE
STONY BROOK SUB-WATERSHED
FREQUENCY OF EXCEEDING RUNOFF
1.0
.875
.75
.675
.5
.375
.25
.125
600
900
1200
1500
1800
2100
2400
2700
3000
RUNOFF IN MILLION CUBIC FEET

FIGURE IV-7



KEY

QHR-FLOW TO HOBBS BROOK RESERVOIR (RUNOFF)
QHW- " WITHDRAWN FROM HOBBS BROOK RESERVOIR
QSR- " TO (SS+F)
SHR-STORAGE IN HOBBS BROOK
(SS+F)- " " STONY " AND FRESH POND RESERVOIRS
QCS-AMOUNT OF CAMBRIDGE DEMAND MET BY RESERVOIR MANAGEMENT
QMDC-FLOW PROVIDED BY MDC TO AUGMENT CAMBRIDGE SUPPLY
QCD-CAMBRIDGE WATER DEMAND

SIMULATION SCHEMATIC OF STONY BROOK SYSTEM

FIGURE V-1

APPENDICES

APPENDIX TO CHAPTER IV

Hydrology

A. GENERAL

Reference is made to Figure IV-1 showing a schematic of the system. Daily records of the flows Q5 and Q6, plus the elevation of the three reservoirs were available starting in 1938. While there are some gaps in the record, it is more than 90% complete from 1938 to the present.

Rating curves for the three reservoirs are given by Figures IV-2, IV-3 and IV-4.

Records of MDC water purchased (Q8) were provided by the MDC.

It was decided that a monthly water analysis would be adequate for the study. Consequently the reservoir elevations were taken at the end of each month, and the flows were totals for the entire month. Storages and flows were converted to units of million cubic feet. A Computer program was written to process the data and compute the total monthly runoffs, Q01 and Q02. The thirty year monthly records of Q01, Q02, Q10 through Q9 and the reservoir storages and levels were processed and printed by an IBM 7094 computer at the Hanscom Air Force Base. Details of the computational process are presented in the following section.

B. COMPUTATION OF INFLOWS

1. Given Quantities

Referring to the schematic diagram Figure IV-1, Q2, Q5, Q6, Q8, S1, S2, and S3 are given in units of million cubic feet per month for flows (Q) and million cubic feet for storages (S).

2. Assumed Evaporation

Evaporation of surface water from the reservoirs must be considered. A typical annual evaporation vector was employed for each year record.

TABLE IV-1

Evaporation

Month	Inches of Evaporation
January	.1
February	.2
March	1.0
April	2.5
May	4.0
June	5.0
July	6.0
August	5.0
September	3.3
October	1.9
November	0.5
December	0.2

These figures are based upon pan evaporation estimates provided by Linsley and Franzini, "Water Resources Engineering", McGraw Hill, 1964 for Seattle, Washington and Ithaca, New York. They were converted to units of million cubic feet per month by entering the rating curve for each reservoir and determining the quantity of water represented by the drawdown. These computations were performed continuously by the computer as the record was processed. Therefore the evaporation volume is based upon a drawdown starting with the elevation of the current month.

3. Washwater

While washwater varied from month to month, it was considered too small a quantity to justify the time it would take to copy the figure from the Cambridge record. Instead, a figure of 2% of the sum of Q5 and Q6 was taken as the washwater constant. This washwater was returned to Fresh Pond Reservoir.

4. Consequences of Incomplete Record

Unfortunately no record of the spill at Hobbs Brook Reservoir was available (Q1). With Q1 unknown, the conservation equations at the six nodes of the system yielded seven unknowns. In order to solve for Q01 and Q02, it was necessary to add a seventh equation which required that Q01 and Q02 be proportioned in the ratio of the catchment areas drained.

5. <u>The Conservation Equations</u>

The six conservation equations and the ratio equations are written below after defining the differences DS1, DS2, DS3.

DS1 = S1 (this month) - S1 (last month)		(Hobbs Brook Reservoir)
DS2 = S2 (this month) - S2 (last month)		(Stony Brook Reservoir)
DS3 = S3 (this month) - S3 (last month)		(Fresh Pond Reservoir)
$Q7 = 0.98\ (Q5+Q6)$	(1)	(Outflow from treatment plant)
$Q9 = Q7+Q8$	(2)	(Supply to Cambridge)
$Q4 = Q6+DS3+EV3 - .02Q7$	(3)	
$Q3 = Q4+Q5$	(4)	
$Q02 = -Q1+Q2+Q3+DS2+EV2$	(5)	(Inflow to Stony Br. Res.)
$Q01 = Q1+DS1+EV1$	(6)	(Inflow to Hobbs Br. Res.)
$Q01 = .37\ Q02$	(7)	

The first three equations may be solved immediately. The last three then represent three equations in three unknowns, Q01, Q02, and Q1.

Solving one obtains:

$$Q02 = (1.0/1.37)\ (Q2+Q3+DS2+EV2+EV1) \qquad (8)$$

Thus Q02 is expressed in terms of known quantities, and Q01 and Q1 may be found from (6) and (7).

6. <u>Role of Computer</u>

It is interesting to evaluate the role of the computer in these calculations. The input was provided via punched cards containing the following pieces of information for each month of record:

Q5 in million gallons/day
Q6 in million gallons/day
Q2 in million gallons/day
S1 in feet of elevation
S2 in feet of elevation
S3 in feet of elevation
EV1, EV2, EV3 in feet of elevation

There were 360 months of record for a total of 360 x 6 = 2160 individual bits of information. Q5 and Q6 were converted to million cubic feet/month requiring multiplication by (1.0/7.48) ft/gallon and the number of days in the month while Q2 had to be multiplied by (1.0/7.48). For each reservoir elevation in feet the storage in million cubic feet was computed from subroutines which provided the equivalent of the respective rating curves. Then the differences DS1, DS2 and DS3 were computed. The evaporations EV1, EV2 and EV3 required six additional "rating curve lookups" plus three subtractions to convert evaporation in feet to million cubic feet. Finally the computations of equations (1), (4), (8) and (7) were performed in that order.

The total number of operations may be evaluated using the following table:

TABLE IV-2

Number of Operations

Computation Element	Number of Operations
Conversion of Q6	360 x 2 = 720
Conversion of Q2	360 x 1 = 360
Conversion of S1	360 x 1 = 360
Conversion of S2	360 x 1 = 360
Conversion of S3	360 x 1 = 360
Conversion of EV1, EV2 and EV3	360 x 9 = 3240
Computation of DS1, DS2, DS3	360 x 9 = 3240
Computation of eq (1)	360 x 3 = 1080
Computation of eq (2)	360 x 2 = 720
Computation of eq (3)	360 x 5 = 1800
Computation of eq (4)	360 x 2 = 720
Computation of eq (8)	360 x 7 = 2520
Computation of eq (7)	360 x 1 = 360
Computation of eq (6)	360 x 3 = 1080
TOTAL	= 17640

It is estimated that hand performance of these computations would have taken at least 20 man-days not including additional time that may have been a consequence of errors.

Writing the program and getting it to work took about 3 man-days of effort although it was approximately two weeks before the programming was completed owing to a twenty-four hour turn-around time at the computation center. Actual computation time on the computer was .33 minutes (20 seconds).

7. Results of the Computation

The complete computational record covering the 360 month period is too lengthy to be included in the report. An extract of twenty years of inflow data is included with the simulation study which appears in the next chapter (Table V-3) Appendix. Unless otherwise noted, any quantative data in this report is based upon the computer record which is part of the office file on the Charles River Study.

Occasionally a negative net inflow resulted. This occurred during periods of extremely low rainfall when there was an excess of evaporation over runoff.

C. SUPPLEMENTARY HYDROLOGIC DATA

1. Purpose

Owing to gaps in the Cambridge City Data, the total annual inflow, used in the preparation of Figure III-1, could not be determined for some of the years of record. Therefore, indirect methods of estimating the unknown quantities were used. These consisted simply of graphical regressions between (1) the known portion of the record with Boston rainfall; and (2) the known portion of the record with Charles River runoff at Charles River Village. A secondary purpose was to compare the annual statistics of the Hobbs Sub-basin with the Charles River Basin.

A runoff frequency curve is presented as a useful way of viewing the system's properties on an annual basis.

2. Rainfall-Runoff Regression

Figure IV-5 displays a wide spread in the data in the high rainfall region and a clustering of points in the low rainfall region. No attempt is made to explain the scatter. When the rainfall is less than 45 inches, the annual runoff for the missing years may be estimated with reasonable precision. Otherwise other hydrologic conditions must be considered. The $\pm$ 4.5 inch confidence interval was arbitrarily chosen as the region in which extrapolated data is likely to lie with a probability of approximately 75-80%.

3. Runoff-Runoff Regression

Figure IV-6 displays a spread similar in character to the rainfall-runoff regression. Neither figure is clearly superior as a means of synthesizing data below 30 inches. Above 30 inches the rainfall-runoff regression offers a better approximation.

4. Frequency Curve

The frequency curve of annual runoff exceedance, Figure IV-7, is based upon the computer record of annual inflows plus data extrapolated from the previous two figures back to 1931. The extrapolated years are 1931-1937, 1952, 1954, 1960, 1964, and 1965.

It is noted that the Cambridge projected demand of 1144 million cubic feet is exceeded with a frequency of .375. In other words the system will supply an inflow that exceeds the projected demand with a probability of 37.5% in any random water year, and Cambridge will have to buy water with a probability of 62.5%.

D. SOURCES OF ERROR

There are several factors in the hydrologic balance that will not be considered in detail, but whose effect was either approximated or neglected. These are enumerated below.

1. Evaporation

Evaporation varies with meteorological conditions and is not constant from year to year.

2. Washwater

Washwater is a variable depending upon operating conditions in any month.

3. Surface Runoff to Fresh Pond Reservoir

The catchment area at Fresh Pond Reservoir was assumed small enough to be neglected.

4. Leakage From Stony Brook Reservoir

An unknown quantity of water seeps through a permeable stratum to the Charles River. This quantity was assumed negligible.

5. Seepage to Fresh Pond From Aberjona River

There is evidence that some seepage occurs from the Aberjona River (Winchester & Woburn) to Fresh Pond. It was not possible to estimate this quantity. However it appeared reasonable to assume that the quantity is negligible.

6. Net Effect of Factors Upon Computations

Items 1 and 2 introduce small random errors whose long range effects are negligible. Items 3 and 5 imply a gain in available system water. This is offset by Item 4, which implies a loss of system water. It is impossible to estimate the net expected error from all of these sources. In view of the fact that computed annual runoff for the sub-basin as a whole is consistent with Charles River at Charles River Village (Figure IV-6) the results we considered adequate for purpose of subsequent engineering analysis.

APPENDIX TO CHAPTER V

TABLE V-3
SIMULATION OF STONY BROOK SYSTEM

MONTHLY OPERATING DATA FOR 20 YEAR PERIOD

1. YEAR OF RECORD
2. MONTH OF RECORD
3. FLOW INTO HOBBS BROOK RESERVOIR
4. FLOW INTO STONY BROOK RESERVOIR
5. TOTAL FLOW INTO HOBBS AND STONY BROOK RESERVOIRS(3+4)
6. CAMBRIDGE DEMAND
7. MONTHLY SURPLUS OR DEFICIT (5-6)
   MINUS IN COLUMN 7 INDICATES DEFICIT
8. STORAGE AT HOBBS BROOK RESERVOIR
   MAXIMUM STORAGE IN HOBBS IS 375 MILLION CUBIC FEET
9. STORAGE AT STONY BROOK AND FRESH POND RESERVOIRS
   MAXIMUM STORAGE IN STONY AND FRESH POND RES IS 230 MILLION CU FT
10. FLOW SUPPLIED BY MDC TO CAMBRIDGE
11. SPILLAGE AT STONY BROOK TO THE CHARLES RIVER
12. AMOUNT OF CAMBRIDGE DEMAND MET BY CAMBRIDGE SUPPLY

DIMENSIONS OF COLUMNS 3 TO 12 ARE MILLION CUBIC FEET/MONTH

1 YR	2 MO	3 QHR	4 QSR	5 TRS	6 QCD	7 S-D	8 SHB	9 SS+F	10 QMDC	11 QSPS	12 QCS
1937	11	12	44	56	94	-38	125	37	0	0	94
1937	12	63	101	164	93	71	188	45	0	0	93
1938	01	41	99	140	90	50	229	54	0	0	90
1938	02	37	101	138	92	46	266	63	0	0	92
1938	03	32	92	124	90	34	296	65	0	0	90
1938	04	18	62	80	85	-5	296	60	0	0	85
1938	05	19	73	92	96	-4	296	56	0	0	96
1938	06	10	53	63	86	-23	296	18	0	15	86
1938	07	43	147	190	94	86	370	30	0	0	94
1938	08	19	77	96	100	-4	335	26	0	35	100
1938	09	21	74	95	112	-17	316	13	0	15	112
1938	10	24	68	92	112	-20	296	13	0	0	112
1938	11	16	47	63	94	-31	265	13	0	0	94
1938	12	36	99	135	93	42	307	13	0	0	93
1939	01	20	53	73	90	-17	290	13	0	0	90
1939	02	31	86	117	92	25	315	13	0	0	92
1939	03	22	66	88	90	-2	313	13	0	0	90
1939	04	40	121	161	85	76	370	32	0	0	85
1939	05	18	69	87	96	-9	370	23	0	0	96
1939	06	02	32	34	86	-52	313	13	0	15	86
1939	07	-13	10	-3	94	-97	185	13	0	31	94
1939	08	0	20	20	100	-80	185	13	80	0	20
1939	09	01	17	18	112	-94	129	13	56	0	56
1939	10	04	18	22	112	-90	133	31	112	0	0
1940	11	15	43	58	94	-36	133	31	36	0	58
1940	12	12	33	45	93	-48	103	13	0	0	93
1940	01	15	42	57	90	-33	70	13	0	0	90

1940	02	21	57	78	92	-14	56	13	0	0	92
1940	03	48	131	179	90	89	104	54	0	0	90
1940	04	80	176	256	85	171	184	145	0	0	85
1940	05	26	89	115	96	19	203	145	0	0	96
1940	06	09	50	59	86	-27	203	103	0	15	86
1940	07	01	33	34	94	-60	185	26	0	35	94
1940	08	-5	12	07	100	-93	185	13	80	0	20
1940	09	02	21	23	112	-89	96	13	0	0	112
1940	10	01	11	12	112	-100	96	13	100	0	12
1940	11	19	53	72	94	-22	115	66	94	0	0
1940	12	21	57	78	93	-15	115	51	0	0	93
1941	01	23	63	86	90	-4	115	47	0	0	90
1941	02	25	70	95	92	03	115	44	0	0	92
1941	03	28	75	103	90	13	128	44	0	0	90
1941	04	19	64	83	85	-2	128	42	0	0	85
1941	05	08	43	51	96	-45	136	30	41	0	55
1941	06	01	28	29	86	-57	137	13	45	0	41
1941	07	-2	21	19	94	-75	135	13	73	0	21
1941	08	-1	18	17	100	-83	134	13	82	0	18
1941	09	01	16	17	112	-95	84	13	45	0	50
1941	10	03	16	19	112	-93	84	13	93	0	29
1941	11	06	19	25	94	-69	90	32	94	0	0
1941	12	11	29	40	93	-53	101	61	93	0	0
1942	01	14	39	53	90	-37	115	31	21	0	69
1942	02	25	67	92	92	0	140	10	4	0	88
1942	03	70	179	249	90	159	210	99	0	0	90
1942	04	33	82	115	85	30	243	96	0	0	85
1942	05	12	49	61	96	-35	243	61	0	0	96
1942	06	09	45	54	86	-32	228	29	0	15	86
1942	07	05	39	44	94	-50	183	09	0	15	94
1942	08	05	35	40	100	-60	188	09	65	0	35
1942	09	02	19	21	112	-91	97	09	0	0	112
1942	10	07	26	33	112	-79	104	10	87	0	25
1942	11	17	48	65	94	-24	121	58	94	0	0
1942	12	51	114	165	93	72	172	79	0	0	93
1943	01	35	78	113	90	23	207	67	0	0	90
1943	02	27	75	102	92	10	234	50	0	0	92
1943	03	49	129	178	90	88	283	89	0	0	90
1943	04	28	77	105	85	20	311	81	0	0	85
1943	05	38	99	137	96	41	349	84	0	0	96
1943	06	10	54	64	86	-22	359	37	0	15	86
1943	07	-2	25	23	94	-71	269	23	0	35	94
1943	08	-3	15	12	100	-88	185	10	0	9	100
1943	09	02	20	22	112	-90	95	10	0	0	112
1943	10	10	34	44	112	-68	105	44	112	0	0
1943	11	16	44	60	94	-34	121	88	94	0	0
1943	12	11	31	42	93	-51	132	26	93	0	0
1944	01	10	28	38	90	-52	142	13	49	0	41
1944	02	22	61	83	92	-9	164	10	28	0	64
1944	03	33	93	126	90	36	197	13	0	0	90
1944	04	39	112	151	85	66	236	40	0	0	85
1944	05	14	54	68	96	-28	250	12	14	0	82
1944	06	07	41	48	86	-38	197	12	0	15	41
1944	07	03	35	38	94	-56	185	12	59	15	35

1944	08	0	20	20	100	-80	185	12	80	0	20
1944	09	11	43	54	112	-58	112	12	0	15	112
1944	10	12	31	43	112	-69	124	12	71	0	31
1944	11	15	41	56	94	-38	139	53	94	0	0
1944	12	35	94	129	93	36	174	54	0	0	93
1945	01	36	89	125	90	35	210	53	0	0	90
1945	02	18	50	68	92	-26	210	27	0	0	92
1945	03	53	147	200	90	110	263	84	0	0	90
1945	04	29	57	86	85	01	292	56	0	0	85
1945	05	66	86	152	96	56	358	46	0	0	96
1945	06	18	75	93	86	07	370	41	0	0	86
1945	07	05	45	50	94	-44	291	41	0	35	94
1945	08	14	62	76	100	-24	232	41	0	35	100
1945	09	11	30	41	112	-71	135	41	0	15	112
1945	10	08	29	37	112	-75	143	30	72	0	40
1945	11	10	29	39	94	-55	153	15	50	0	44
1945	12	55	150	205	93	112	208	72	0	0	93
1946	01	59	159	218	90	118	267	131	0	0	90
1946	02	46	125	171	92	79	313	164	0	0	92
1946	03	102	82	184	90	94	375	192	0	0	94
1946	04	13	47	60	85	-25	375	167	0	0	85
1946	05	35	116	151	96	55	375	222	0	0	96
1946	06	10	53	63	86	-23	375	184	0	15	86
1946	07	08	53	61	94	-33	375	116	0	35	94
1946	08	-2	35	33	100	-67	340	49	0	35	100
1946	09	14	52	56	112	-56	269	49	0	15	112
1946	10	21	64	85	112	-27	269	22	0	0	112
1946	11	10	28	38	94	-56	213	22	0	0	94
1946	12	03	09	12	93	-81	132	22	0	0	93
1947	01	34	92	126	90	36	156	24	0	0	90
1947	02	24	66	90	92	-2	156	22	0	0	92
1947	03	43	119	162	90	72	199	51	0	0	90
1947	04	28	86	114	85	29	227	52	0	0	85
1947	05	39	97	136	96	40	266	53	0	0	96
1947	06	11	56	67	86	-19	251	34	0	15	86
1947	07	-11	12	01	94	-93	185	20	8	0	86
1947	08	09	33	42	100	-58	180	10	43	0	57
1947	09	07	34	41	112	-71	109	10	0	0	112
1947	10	0	7	7	112	-105	109	17	112	0	0
1947	11	17	47	64	94	-30	126	64	94	0	0
1947	12	20	54	74	93	-19	126	45	0	0	93
1948	01	17	46	63	90	-27	126	18	0	0	90
1948	02	26	70	96	92	04	130	18	0	0	92
1948	03	65	180	245	90	155	195	108	0	0	90
1948	04	56	102	158	85	73	251	125	0	0	85
1948	05	21	78	99	96	03	272	107	0	0	96
1948	06	33	113	146	86	60	305	134	0	0	86
1948	07	20	85	105	94	11	325	125	0	0	94
1948	08	-1	22	21	100	-79	276	60	0	35	100
1948	09	-4	4	0	112	-112	184	25	0	15	112
1948	10	04	20	24	112	-88	184	10	73	0	39
1948	11	20	57	77	94	-17	167	10	0	0	94
1948	12	16	45	61	93	-32	135	10	0	0	93
1949	01	23	61	84	90	-6	129	10	0	0	90

1949	02	35	95	130	92	38	164	13	0	0	92
1949	03	53	147	200	90	110	217	70	0	0	90
1949	04	32	99	131	85	46	249	84	0	0	85
1949	05	16	65	81	96	-15	249	69	0	0	96
1949	06	-2	21	19	86	-67	206	30	0	15	86
1949	07	-4	21	17	94	-77	185	10	36	0	58
1949	08	-4	12	08	100	-92	175	05	77	0	23
1949	09	13	50	63	112	-49	101	15	64	15	48
1949	10	08	31	39	112	-73	109	46	112	0	0
1949	11	13	37	50	94	-44	122	83	94	0	0
1949	12	16	45	61	93	-32	122	51	0	0	93
1950	01	27	75	102	90	12	149	36	0	0	90
1950	02	25	50	75	92	-17	149	19	0	0	92
1950	03	53	146	199	90	109	202	75	0	0	90
1950	04	34	106	140	85	55	236	96	0	0	85
1950	05	15	61	76	96	-20	236	76	0	0	96
1950	06	0	24	24	86	-62	200	35	0	15	86
1950	07	-5	12	7	94	-87	185	15	52	0	42
1950	08	5	36	41	100	-59	175	5	39	0	61
1950	09	6	30	36	112	-76	99	5	0	0	112
1950	10	13	42	55	112	-67	112	47	112	0	0
1950	11	10	30	40	94	-54	122	77	94	0	0
1950	12	32	86	118	93	25	154	70	0	0	93
1951	01	35	94	129	90	39	189	74	0	0	90
1951	02	50	137	187	92	95	239	119	0	0	92
1951	03	55	155	210	90	120	294	184	0	0	90
1951	04	89	253	342	85	257	375	230	0	130	85
1951	05	28	96	124	96	28	375	230	0	28	96
1951	06	15	66	81	86	-5	375	210	0	15	86
1951	07	-2	27	25	94	-69	375	106	0	35	94
1951	08	5	38	43	100	-57	325	64	0	35	100
1951	09	-4	6	2	112	-110	224	30	0	15	112
1951	10	16	52	68	112	-44	195	15	0	0	112
1952	11	7	22	29	94	-65	130	15	0	0	94
1952	12	21	56	77	93	-22	118	5	0	0	93
1953	01	36	97	135	90	45	154	14	0	0	90
1953	02	41	111	152	92	60	195	33	0	0	92
1953	03	61	139	200	90	110	256	82	0	0	90
1953	04	37	124	161	85	76	293	121	0	0	85
1953	05	29	98	127	96	31	322	123	0	0	96
1953	06	4	37	41	86	-45	322	63	0	15	86
1953	07	-3	23	20	94	-74	243	33	0	35	94
1953	08	-4	10	6	100	-94	185	15	0	17	100
1953	09	6	18	24	112	-88	97	15	0	0	112
1953	10	-3	0	-3	112	-115	94	15	112	0	0
1953	11	39	108	147	94	53	133	29	0	0	94
1953	12	55	144	204	93	111	188	85	0	0	93
1954	01	24	66	90	90	0	188	85	0	0	90
1954	02	28	76	104	92	12	216	69	0	0	92
1954	03	55	154	209	90	119	271	133	0	0	90
1954	04	58	169	227	85	142	329	217	0	0	85
1954	05	41	131	172	96	76	370	230	0	22	96
1954	06	26	95	121	86	35	375	230	0	30	86
1954	07	-2	25	23	94	-71	375	124	0	35	94

1954	08	01	28	29	100	-71	369	24	0	35	100
1954	09	55	154	219	112	107	375	125	0	0	112
1954	10	20	65	85	112	-27	375	98	0	0	112
1954	11	125	340	465	94	371	375	230	0	239	94
1954	12	151	408	559	93	466	375	230	0	466	93
1955	01	28	76	104	90	14	375	230	0	14	90
1955	02	33	89	122	92	30	375	230	0	30	92
1955	03	79	218	297	90	207	375	230	0	207	90
1955	04	47	141	188	85	103	375	230	0	103	85
1955	05	32	106	138	96	42	375	230	0	42	96
1955	06	8	47	55	86	-31	360	199	0	15	86
1955	07	1	33	34	94	-60	360	104	0	35	94
1955	08	66	205	271	100	171	375	230	0	30	100
1955	09	25	85	110	112	-2	375	213	0	15	112
1955	10	65	185	250	112	138	375	230	0	0	112
1955	11	87	238	325	94	231	375	230	0	231	94
1955	12	14	39	53	93	-40	375	190	0	0	93
1956	01	36	98	134	90	44	375	230	0	4	90
1956	02	46	125	171	92	79	375	230	0	79	92
1956	03	51	143	184	90	94	375	230	0	94	90
1956	04	53	157	210	85	125	375	230	0	125	85
1956	05	122	351	473	96	377	375	230	0	377	96
1956	06	17	73	90	86	4	375	230	0	4	86
1956	07	-1	24	23	94	-71	369	130	0	15	94
1956	08	1	23	24	100	-76	300	88	0	35	100
1956	09	2	20	22	112	-90	240	43	0	15	90
1956	10	8	29	37	112	-75	190	18	0	0	112
1956	11	6	17	23	94	-71	170	10	53	0	41
1956	12	22	59	81	93	-12	160	8	0	0	93
1957	01	29	79	108	90	18	178	19	0	0	90
1957	02	44	73	117	92	25	203	19	0	0	92
1957	03	38	106	146	90	56	241	37	0	0	90
1957	04	44	107	153	85	68	285	61	0	0	85
1957	05	18	57	75	96	-21	285	40	0	0	96
1957	06	1	25	26	86	-60	230	20	0	15	86
1957	07	0	26	26	94	-68	185	10	13	0	81
1957	08	01	23	24	100	-76	175	5	61	0	39
1957	09	6	26	32	112	-80	95	5	0	0	112
1957	10	10	31	41	112	-71	105	36	112	0	0
1957	11	09	26	35	44	-59	114	15	47	0	47
1957	12	24	65	89	93	-6	114	9	0	0	93
1958	01	104	232	236	90	143	218	48	0	0	90
1958	02	72	196	268	92	176	290	152	0	0	92
1958	03	186	507	693	90	603	375	230	0	436	90
1958	04	173	479	652	85	567	375	230	0	567	85
1958	05	154	450	609	96	513	375	230	0	513	96
1958	06	14	63	77	86	-9	370	226	0	0	86
1958	07	3	39	42	94	-52	335	174	0	35	94
1958	08	4	37	41	100	-59	300	115	0	35	100
1958	09	5	47	52	112	-60	285	55	0	15	112
1958	10	15	50	65	112	-47	253	40	0	0	112
1958	11	17	47	64	94	-30	223	40	0	0	94
1958	12	24	69	93	93	0	223	40	0	0	93